Modeling the Resource Consumption of Housing in New Orleans using System Dynamics

by

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ABSTRACT

This work uses Systems Dynamics as a methodology to analyze the resource requirements of New Orleans as it recovers from Hurricane Katrina. It examines the behavior of the city as a system of stocks, flows and time delays at a macro-level. The models used to simulate this behavior are compared to historic data. The construction materials, energy and labor required to construct several different types of housing systems are examined and these data are combined with the macro-scale analysis of the city. Several alternative scenarios are proposed based on the interactions of feedback loops identified.

Thesis Supervisor: John E. Fernández

Title: Associate Professor of Building Technology

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Preface

Several groups and individuals collaborated on this project. These were:

- Dr. Earthea Nance - Office of Recovery Management (ORM)
- Alek Cannan, Kirk Westphal and Enrique Lopezcalva - Camp Dresser McKee (CDM)
- Edward Connolly - New Ecology Inc (NEI)
- Prof. John Fernandez, David Quinn - Massachusetts Institute of Technology (MIT)

These groups were originally brought together in Fall 2006 by Will Bradshaw (founder of Green Coast Enterprises). CDM provided their expertise in the field of systems modeling and developed a model to represent the housing stock in New Orleans. Alek Cannan worked on this model with Kirk Westphal and Enrique Lopezcalva, who all provided valuable advice. In addition, Edward Connolly provided useful guidance. Prof. John Fernandez and David Quinn worked on all aspects of this project. The focus of this project evolved over time, influenced by priorities that were identified by the ORM. Figure 1 illustrates the chronology of this project. Dr. Nance provided valuable critiques of this work and many useful suggestions.

The work is on an ongoing process and it is hoped that it will be of assistance to the ORM, as well as the City of New Orleans. All data and models will be made available to the public via the website www.nolamaterial.com.

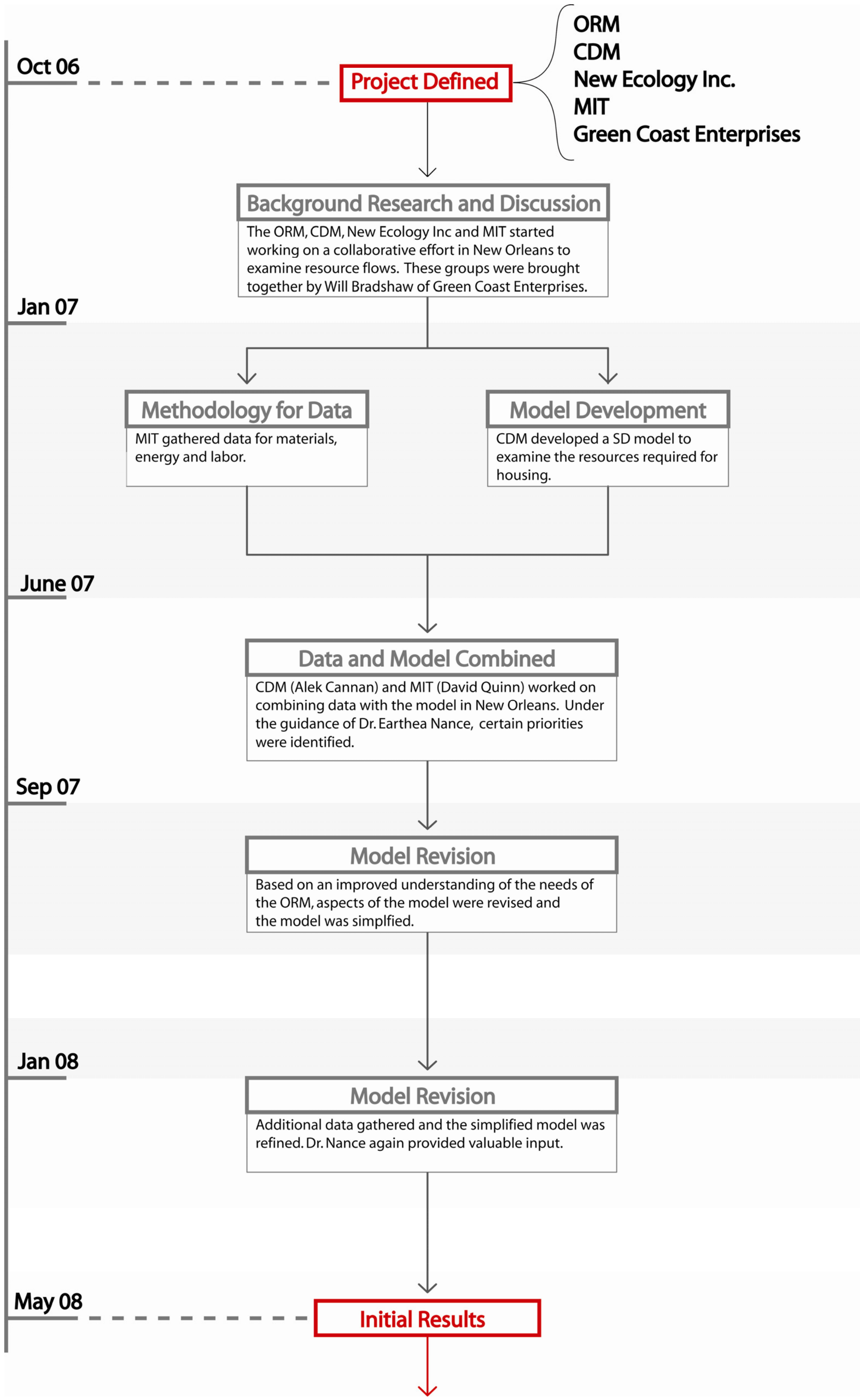

Figure 1: Timeline of Project

Acknowledgments

I would like to thank my thesis supervisor, Prof. John Fernández for his support and guidance over the course of this project.

I would like to thank all the people who assisted me with this work by providing data, advice and suggestions.

I would also like to thank my friends and family for their support and encouragement.

1 Background

The goal of this thesis is to develop an urban System Dynamics model which simulates the flow of resources used in the residential construction sector in New Orleans. The three resources examined are construction materials, energy and labor. The aim of this research is to quantify and improve the efficiency of these flows for residential construction. This model is intended to assist with policy-making decisions that relate to housing by illustrating this information graphically and numerically using data from New Orleans. It examines the current situation for a small sample area within New Orleans, and based on this data considers future possible scenarios. It is hoped that this analysis will help to identify possible opportunities for improving the resource efficiency of the city, in addition to improving the local economy.

New Orleans is a particularly relevant case study for examining the resource consumption of housing, as there was and still is a need for large amounts of housing due to the damage caused by several hurricanes during late 2005. This city also has the additional challenge of a large percentage of the population (27.9%) who are below the poverty line (Masozera 2006 and US Census 2000a) which makes it harder to implement environmental policies that have an additional cost.

This study hopes to assist with the housing reconstruction effort by data collection, analysis of existing housing and the identification of policies which could assist with social, economic and environmental improvements.

1.1 Analysis of Cities, Sustainability and the Built Environment

Cities are both sites which concentrate demands for natural resources, and sites which generate the greatest amount of industrial waste. Globally, they are estimated to contain more than 50% of the total world population, which is currently 6.68 billion (US Census 2008a). The relationship between cities and their host environment has been described as parasitic (Girardet 1996) with most cities historically having taken essentials without giving anything in return, which is come cases, caused their own demise. This has happened to the earliest large cities, and is considered to be a contributing factor in the fall of Rome (100 AD) with a population of one million, and Teotichuacan (450 AD) with a population of 140, 000 (Girardet 1996). The reason that modern cities have not yet met the same fate while behaving in a similar manner is due to the availability and use of fossil fuels, which are essentially a stored form of solar energy. This energy source allows resources to be drawn from ever greater distances, and allows energy-intensive processes to occur which provide the essentials that are needed for cities' survival. Dougherty and Hammond (2004) argue that a city ultimately cannot be sustainable as the "outlying support structure extends from the regional to national and even global scale". However, the structure of the urban fabric and the geographic location of the city influence the resources consumed. By focusing on resource efficiency, energy conservation and the environmental impact, the goal of making a city more sustainable would be to minimize the land area that it relies upon for survival. It is necessary to understand how cities "are integrated within a larger environmental and social context" so that the policies necessary to shape the future of cities are better understood (Coelho 2007).

Doughty and Hammond (2004) proposed four principles that need to be satisfied to achieve sustainability[1]:

> "*Condition 1:* Finite materials (including fossil fuels) should not be extracted at a faster rate than they can be re-deposited in the Earth's crust.
>
> *Condition 2:* Artificial materials (including plastics) should not be produced at a faster rate than they can be broken down by natural processes.
>
> *Condition 3:* The biodiversity of ecosystems should be maintained, whilst renewable resources should only be consumed at a slower rate than they can be naturally replenished.
>
> *Condition 4:* Basic human needs must be met in an equitable and efficient manner."

The following sections describe the concepts and methodologies used in this analysis. The goal of these methodologies is to examine the urban metabolism of a city as it provides the conceptual framework where Industrial Ecology, Material-Flow Analysis and System Dynamics can be applied.

1.2 The Urban Metabolism

The concept of a city as an organism with metabolic processes was first described by Wolman (Wolman 1965). Graedel (1999) also described cities as being analogous to organisms; they

[1] These principles are based on the Swedish expert who developed The Natural Step, Karl-Henrick Robért

consume nutrients and energy, store resources for later use, and produce waste. Thus, examining the metabolic flows of cities allow us to consider at what rate resources are being depleted and at what rate waste is being produced. In the case of the built environment the metabolic flows are raw material, energy and water which are transformed into building stocks with an outflow of waste (Wolman 1965).Conceptually, examining the urban metabolism is a study of the flow of matter and energy within the city which illustrates trends in human energy consumption and material usage. Fischer-Kowalski and Huttler (1999) defined urban metabolism as:

Sum of Material and Energetic Inputs = Sum of Outputs + Changes in Stock

Huang (2003) defines the urban metabolism as the process of transforming all the materials and commodities for sustaining the city's economic activity.

Analysis of the urban metabolism can assist in decision-making regarding resource usage, pollution, material efficiency and closing of material cycles. In the short term, this becomes more relevant within cities that have tightly defined natural boundaries where the resource constraints are easy to identify, but it is also important for long term sustainability. As we evaluate cities while considering the policy perspectives, metabolic studies can provide the basis for discussions of the desirability of changes in the scale or type of a city's metabolism, and how such changes might best be accomplished (Graedel 1999). At a global scale, this is also relevant as we are approaching a time when more than 50% of the global population lives in cities. This increasing urbanization will make us more aware of the earth being a closed ecosystem, with the only additional input of solar energy. This constraint will become more apparent when fossil fuel reserves diminish to a level where there is a reliance on renewable fuel sources. Modern megacities will start to reach equilibrium only when these global fossil fuel reserves are exhausted and global water and food are utilized to the maximum level possible (Decker 2000). Examining the built environment of cities is particularly relevant as the construction industry uses in excess of 40% of all extracted material resources in creating buildings (Kibert 2002, quoting Ausbel).

1.3 Industrial Ecology

Industrial ecology is the "systematic analysis and design of human activities and the environment with the implicit goal of optimizing the total industrial cycle: from raw material input through the creating of a finished product to waste output and back to the economy" (Coelho 2007). Industrial ecology views human systems as being analogous to natural systems. For these systems to be sustainable, they need to function 'not in isolation from [their] surrounding systems but in concert with them' (Graedel and Allenby 2003). Industrial ecology is a well-defined theoretical field (Haberl 2001; Haberl 2002), and examples of the application of these principles are becoming more common. One such example is the development of industrial eco-parks where the waste from one industrial process becomes the raw-material for another process. Frosch and Gallopoulos' article, 'Strategies for Manufacturing' (1989) brought about a renewed interest in the principles of industrial ecology, in addition to several articles which were published by Ayres and Kneese during the 1970's (Graedel and Allenby 2003). Frosch and Gallopoulos' posed the question 'why would not our industrial system behave like an ecosystem, where the wastes of a species may be resource to another species?' which became a catalyst for change in the analysis of human processes.

Although the principles of industrial ecology had been considered since 1885 (Brunner et al. 2004), this perspective has become more widely accepted since the 1970's due to an increasing awareness that views anthropological society within a finite boundary. An illustration of this societal awareness is the fact that the book 'Limits to Growth' (Meadows et al. 1972 and Meadows et al. 2004) became a bestseller. The book focused on human and ecological systems and discussed how we need to consider growth (human population and economic) within the resource constraints of the world. This approach, which by definition has a more holistic view of human and physical systems, requires experts in diverse scientific fields (Fischer-Kowalski 1998). Ultimately, industrial ecology is viewed as a method by which 'humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural and technological evolution' (Graedel and Allenby 2002).

1.4 Material Flow Analysis

Material flow analysis (MFA) is the systematic assessment of stocks and flows of materials within a system defined within space and time (Brunner et al 2004). The principle for this analysis is based on the conservation of matter; inputs, outputs and stocks can be examined.

This is a framework that is used to quantify the use of natural resources. The intention of this analysis is to enable decision-makers to better understand what the effects that a decision based on a single process may have, due to the potentially hidden interactions that may exist (Cooper 2008). Anthropogenic systems consist of more than just material flows and stocks, as these systems need to account for human behavior and needs. Energy, spatial information and socioeconomic issues must also be considered if we are to manage human activities within the anthroposphere in a responsible way.

The work of many MFAs has been focused on the regional or national scale. The publication 'The Weight of Nations' (Hutter et al. 2000) showed detailed material flows for the United States, Japan, Austria, Germany and The Netherlands and provided important data regarding material usage per capita and indicated areas which are of concern. Several key points were identified: 80% of the waste (by weight) is CO_2, one half to three quarters of annual resource inputs are returned to the environment as wastes within a year, and although industrial economies are becoming more efficient in their use of materials, waste generation is continuing to increase. It highlights the fact that there is an enormous lack of knowledge regarding appropriate rates of consumption and material use. It concludes that there is an urgent need for global physical accounts as they "provide an integrated framework for analyzing flows of materials from the natural environment into the human economic system" (Hutter et al. 2000). Eventually, it is thought that standardized input/output balance sheets will be considered as important as typical economic indicators to describe the state of an economy.

The nomenclature from the "Material Flow Analysis Handbook" is included as it defines terms precisely that are used in this study. These are:

- Processes are linked by flows (mass per unit time).
- Flows across boundaries are called imports or exports.
- A system boundary is defined within space and time.
- Stocks are defined as material reservoirs within the analyzed system and have the physical unit of kilograms.
- A process is defined as a transport, transformation or storage of materials.
- A system consists comprises of a set of material flows, stocks and processes within a defined boundary. (Brunner et al. 2004)

1.5 System Dynamics

System Dynamics (SD) is proposed as an appropriate methodology for examining the metabolic flows within a city that are identified as contributing to the urban metabolism, as well as providing a convenient method for illustrating industrial ecology principles and applying material-flow analysis methodology. Forrester pioneered the application of SD which is derived from the scientific principles of control theory, more than 35 years ago (Coyle 1996). Coyle (1996) defines SD below:

> "System dynamics deals with the time-dependant behavior of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policies through simulation and optimization".

SD is also a useful graphical methodology for illustrating linear and nonlinear differential equations, as well as examining the behavior of such systems. Vogstad (2007) describes this as the stock and flow metaphor providing "a language in which the world can be interpreted as an information feedback system within which decision-makers (agents) carry out their policies". Barlas (2002) states several basic principles that should be applied so that it is possible to identify systemic feedback – four of these principles that are considered relevant are described below.

Principle 1: Importance of Causal Relationships

A causal relationship means that the input variable has some causal influence on the output variable. In addition the relationship should identify whether the influence is positive or negative (Sterman 2000, 138). For example, x has a positive relationship with y if an increase in x results in an increase in y. Similarly, x has a negative relationship with y if an increase in x results in a decrease in y. An example of this is an increase in population resulting in an increase in resource consumption, assuming per capita resource consumption does not change.

Principle 2: Importance of Circular Causality

It is important to identify dynamic circular causalities within the system. These loops ultimately result in either positive feedback (exponential growth) or negative feedback (exponential decay). These loops can be described as either positive and self-reinforcing, or as negative and self-correcting (Sterman 2000, 143).

Principle 3: Dynamic behavior pattern identification
This principle emphasizes the fact that most important events result due to an accumulation (stock). The goal is to construct a hypothesis (or model structure) that explains why and how these dynamics patterns were/are generated.

Principle 4: The internal structure causes the behavior of the system
The interaction of the feedback loops in a system should be the primary driver for change to occur in the system. This is due to the model structure of stocks, flows and feedback loops.

Depending on the level of complexity of the system, SD can provide insight into the interactions of the structure, as understanding the effect of feedback is necessary so that the overall behavior of the system can be understood.

Systems Dynamics is a similar method of analysis to MFA, as it uses stocks and flows to describe the state of a system. However, the difference between SD and MFA models is the following. SD models can suggest reasons why specific behaviors occur and simulate the effect of interactions within a complex system, while MFA methodology provides a static snapshot of the current state of the system which is being examined.

2 Urban Analysis and System Dynamics

There are many methods of analysis which are applied to urban environments, such as land use maps, monitoring of physical infrastructure, vehicular traffic monitoring, but few methods focus specifically on resource consumption rates, and the identification of possible constraints. Although there are an increasing number of strategic environmental plans for cities in the US, few studies focus on resource consumption rates within cities with dynamic and holistic perspectives[2]. The complexity of cities and the lack of short term constraints are possible reasons why these topics have not been focused on more. A further complication is the difficulty of acquiring data; gathering real-time, or even recent data, for such complex systems is difficult. Within a city, the causes for certain behaviors in the system may not be obvious, making it difficult to interpret or predict future behavior, as the driving force is often unclear.

In this study, System Dynamics (SD) is proposed as an appropriate methodology for urban analysis, as it provides a means to identify interlinking factors and can combine physical resource issues with social and economic behaviors. As this study was limited to housing, this SD model is useful for calculating what the effects of exogenous inputs are (from other parts of this urban system) but it cannot identify what those inputs should be, as they are outside the bounds of this study. It is hoped that by studying this part of the urban system, it can provide insight into specific aspects of this complex system. In addition, such a model can assist with identifying leverage points in a system.

2.1 Principles of System Dynamics

The elements of SD diagrams are stocks, flows, feedback loops, convertors and time delays. When the boundary of a system is defined, flows which cross the boundary (inputs or outputs) flow to or from a cloud. This is viewed as a stock or a sink with unlimited capacity.

Stocks describe the state of the system at any particular time and are the result of the accumulation of a flow. In this model, houses are viewed collectively as stocks. Typically in a city the stock of housing is slow to change, however, the effects of hurricanes on New Orleans resulted in dramatic changes to the housing stock in a short space of time. Generally, the size

[2] These studies do not necessarily view these issues from a quantitative way, but do typically view the city from a holistic perspective.

and lifetime of a stock gives us a useful indication of how long it will take for a system to correct a problem.

Flows are input or output rates that cause stocks to either increase or decrease and are controlled by a rate variable. This rate variable can be a function of an independent variable, a stock or a combination of both.

Feedback loops are structures within the system which cause the system to behave in a particular way. Feedback loops consist of either 'Reinforcing Loops' or 'Balancing Loops'. Causal loop diagrams are visual representations of feedback loops. These are used to illustrate the chain of causality within the system.

Convertors are a method of defining a variable within a model, or mathematical combinations of other variables. They should be used to add clarity to the diagram.

Time Delays are created within a model by the specific structure of the stocks, flows and convertors and also by some inbuilt functions in SD software.

2.2 Application of System Dynamics to Urban Analysis

SD is suitable for analyzing interactions regarding resource consumption in the urban environment as it is possible to combine human behavior and natural resource constraints within the one model. However, one difficulty with this approach is identifying causal relationships that can be accurately quantified. Due to this uncertainty the analysis becomes more ambiguous. Another difficulty is that the behavior of the system can be strongly influenced by complex external factors (exogenous variables), over which there is little control. An example of this would be an urban SD model for New Orleans that did not consider the effect or frequency of hurricanes.

The majority of published work which applies the methodology of SD to cities is over 30 years old, with the main contributors being Forrester and Alfeld (Forrester 1969 and Alfeld 1976). It appears that this method of analysis has not been widely adopted by planners, engineers or architects when examining urban areas. It is hoped that this work will assist with the standardization of a framework that can be used to analyze cities from an objective and general perspective. Forrester first published *Urban Dynamics in 1969* which analyzed a city using SD (Forrester 1969)*.* This was a controversial book and provoked much discussion among planners as they disagreed with his results and technique[3]. Critics in the planning community rejected the book on the principle that it was not based on data but on proposed relationships from observation (Alfeld 1995). Louis E Alfeld, a colleague of Forrester's was also involved in the subsequent development of this field. After the publication of *Urban Dynamics* there was a project sponsored by U.S. Department of Housing and Urban Development to verify the proposed model. This was unsuccessful for several reasons – insufficient funding, time and reviewers who did not accept the fundamentals of SD contributed to the problems (Alfeld 1995). Forrester published *Urban Dynamics* in 1969 which was followed by Alfeld's publication of *An Introduction to Urban Dynamics* in 1976. Both of these books used SD models to examine hypothetical scenarios within a city. These models were extremely complex, hard to understand and unfortunately were not verified. In addition they were published at a time when few people had access to computers that were powerful enough to replicate the proposed models. This resulted in the methodology being rejected despite the fact that in principle, SD models can be used effectively in both urban and global analysis and policy-making.

Since Alfeld and Forrester's work, there have been several papers published which use System Dynamics to examine specific policies in cities, such as waste (Dyson 2005) and transport (Mehmood 2003). However the approach of modeling an entire city has not attempted since Forrester's work.

2.3 Review of System Dynamics Model for Urban Analysis

For an urban system the overall resource consumption of the region being examined must be capable of being supported within that ecosystem boundary, otherwise it could not be sustained. Schellnhuber (1999) describes the two dangers that can affect models of ecological and human complexity. The first is the danger of over-simplification and the second is the danger of over-sophistication. This is a difficult goal to satisfy for urban analysis as there are few widely accepted appropriate models of urban systems.

[3] This has been recreated using Anylogic software here:
http://www.xjtek.com/anylogic/demo_models/social_dynamics/

As previously mentioned (Section 1.3) an effective illustration of anthropological growth within a finite ecological system is shown in the book, *Limits to Growth* (Meadows et al. 2004). SD models are used to model complex urban infrastructure, such as municipal water systems and combine them with user behavior and policies. Modeling these types of systems with stocks and flows is obvious (and indeed most likely the origin of the methodology), but combining user behavior with this type of physical system enables physical and anthropological systems to interact.

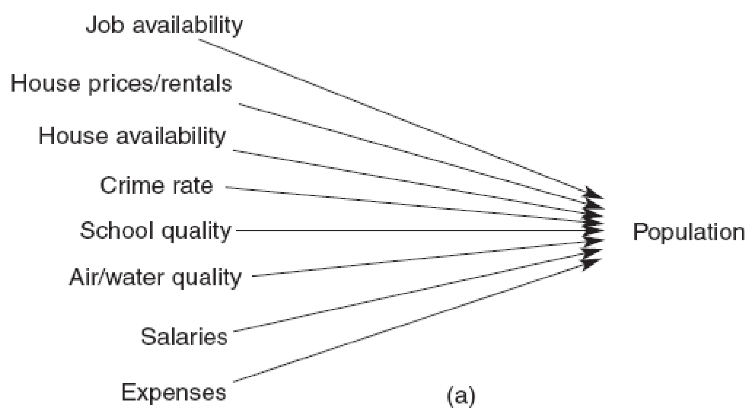

Figure 2: Exogenous, static model of a city's population (Diagram and text from Barlas, 2002)

Figure 2 is an example of an SD model that relies solely on external variables and is described as an exogenous, static model of a city's population (Barlas 2002). Figure 3 illustrates a dynamic, endogenous urban model for a city. In this model there are many causal relationships that are difficult to quantify such as 'Crowding' affecting ''Crime Rate', and 'House availability' being affected by 'Government Investment'. Meadows describes how the most important part of the analysis of a complex system is to identify the leverage points within the system as these are where policy efforts need to be focused on (Meadows 1999). The proposed leverage points for New Orleans are discussed in Chapter 5.

2.4 Problems applying System Dynamics to Urban Analysis

Using a SD model to examine different policies is difficult, when human behavior is involved. The unpredictable aspect of human behavior was not considered in this model, as there is a lack of empirical data available. Studies which quantify relationships between choice and human behavior are usually linked to specific spatial and socio-economic backgrounds and would need to take into account many specific factors with regard to New Orleans. In this way the feedback loops which have been identified have used empirical data where possible to quantify the relationship amongst variables, but in some cases where there was no empirical data assumptions were made.

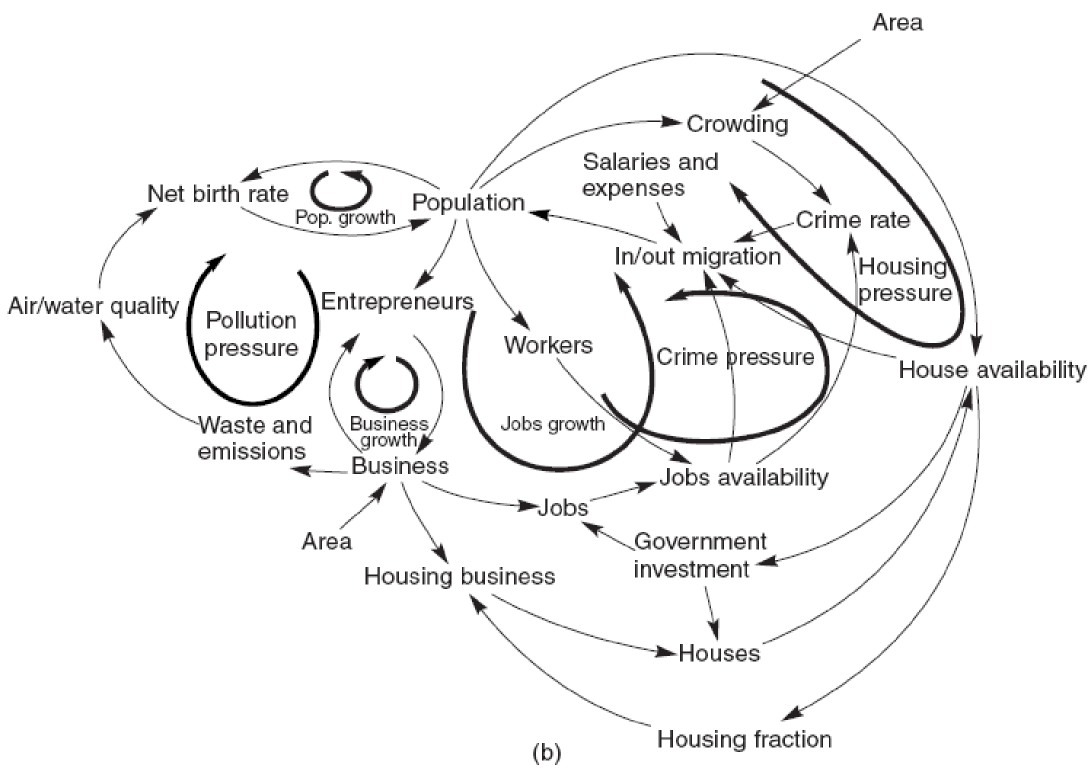

Figure 3: Endogenous, dynamic model of a city's population (Diagram and text from Barlas 2002)

An alternative modeling method, Agent-Based Modeling (ABM) is used to predict how humans will behave according to a set of conditions and can be used to model human behavior within an urban system. For this model, a combination of SD and ABM could be used to simulate the human behavioral aspects of policies. This type of model can better represent human behavior at an individual level and help explain how these behaviors affect the overall system. However, SD is still appropriate for a macro-analysis of specific policies and this was considered to be the priority. An agent-based model was developed for examining what barriers existed to prevent people from returning and rebuilding (Radzicki 2006) however, the results from that study were not relevant to this work.

3 System Dynamics Model – Macro Scale Analysis of New Orleans

This chapter provides a description of the problems that were faced by New Orleans and the proposed model that was developed to look at resource consumption. This analysis views the city as a complex system and tries to identify specific patterns of behavior within this system. It assumes that the city's housing stock was in an equilibrium state before the storm occurred and that after the hurricane, the system would try to return to its equilibrium state. This chapter focuses on specific parameters that can be used to measure the city's return to equilibrium with respect to the housing stock. The details which relate to construction in New Orleans are examined in Chapter 4. Chapter 5 combines the macro-analysis in this chapter with the specific information from Chapter 4 to provide a more detailed analysis with quantitative results.

3.1 Background: New Orleans and Hurricane Katrina

Serious damage was caused to residential housing in New Orleans after it experienced a severe hurricane followed by flooding in August 2005. Over 1500 people died[4] with many more reported missing in the aftermath. The storm brought strong winds and heavy rain to the city and the storm surge which followed, breached several levees that protect New Orleans[5]. The damaged levees allowed water to enter which resulted in up to 80% of the city being flooded[6]. It was estimated that 105,323 housing units were either severely damaged or destroyed within New Orleans parish, which is 56% of the total number of housing units in this area (GNOCDC 2005a). An estimated 450,000 people were made temporarily homeless as a result of the storm. Further damage was caused to the building stock by Hurricanes Rita and Wilma. An estimate of the total amount of construction material required to rebuild all houses damaged using an average house size for New Orleans and wood-stud construction is shown in Table 1. This table is included to illustrate the order of magnitude of material required.

Table 1: Estimate of total material required to reconstruct wood stud houses

Material	**Mass**
	[kg x 10^6]
Concrete	2317
Lumber	1363
Gypsum	779
OSB	763

[4] Louisiana's GIS council, http://lagic.lsu.edu
[5] http://www.cnn.com/SPECIALS/2005/katrina/
[6] http://lagic.lsu.edu

This volume of material is illustrated graphically in Figure 4 using the cross-section of the Superbowl (a domed American football stadium in downtown New Orleans, with a radius of 115 m[7]). The total height of this cylinder of material (considering lumber, concrete, oriented strand board (OSB) and gypsum) is 141m.

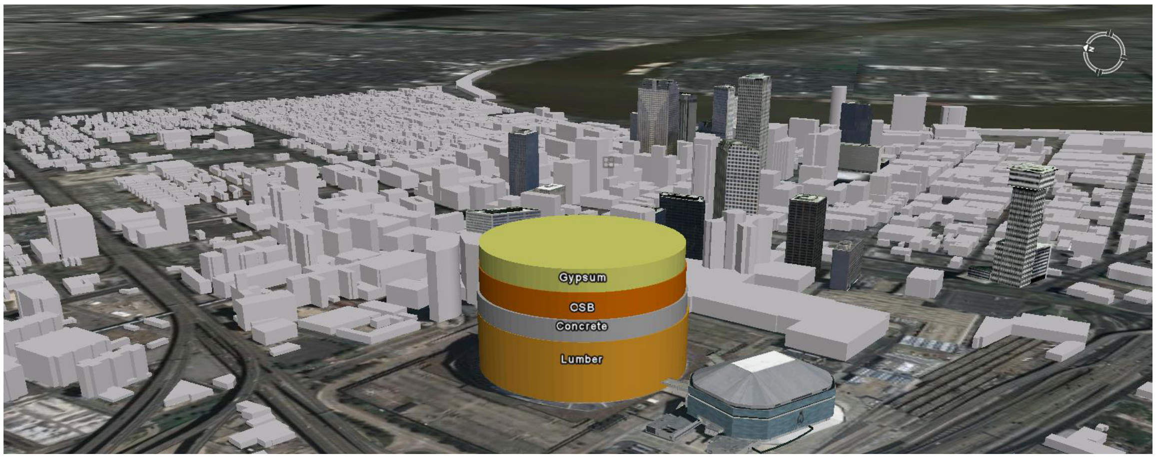

Figure 4: Volume of material required using plan area of Superbowl as a measure (Google Earth)

The total cost of the damage has been estimated to be in the region of $100 billion (GNOCDC 2007b). Over 30 million cubic yards of waste were generated as a result of the hurricane. As the waste is mixed with many contaminants, it is difficult to segregate prior to disposal or possible reuse (EPA 2006). This research aims to identify the effects of constructing houses using different materials and quantifying the resulting material flows. The resources required to build houses using several construction methods (wood stud, steel stud, aerated autoclaved concrete (AAC) and structural insulated panels (SIP)) were analyzed at a micro and macro level, considering the material, energy and labor used (Figure 5 and Figure 6). The specific characteristics of each material (lifespan, embodied energy and environmental impact) were considered as well as reuse or recycling opportunities of different materials. Examining these construction methods in the context of regional material flows, the goal is to contribute towards a reduction of the environmental impact of housing on the resource consumption of the surrounding region. Analyzing all material flows in New Orleans would require a more detailed study of material flow at a city scale. Due to time constraints and the urgent need for housing, this study limited its focus solely to residential construction in the parish of New Orleans.

[7] Measured using ArcGIS USGS orthophotos

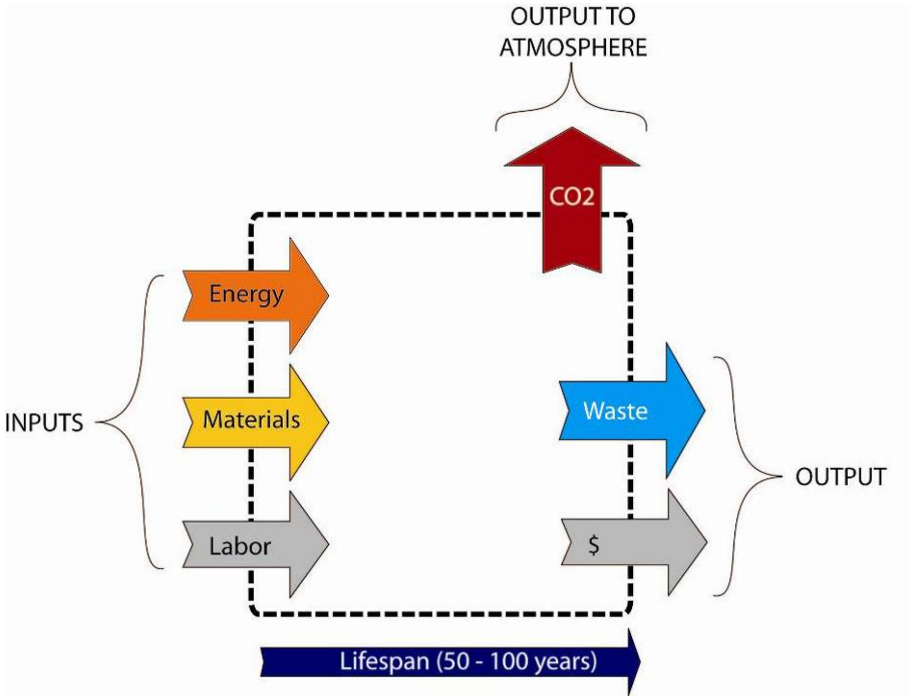

Figure 5: Schematic of resources being examined

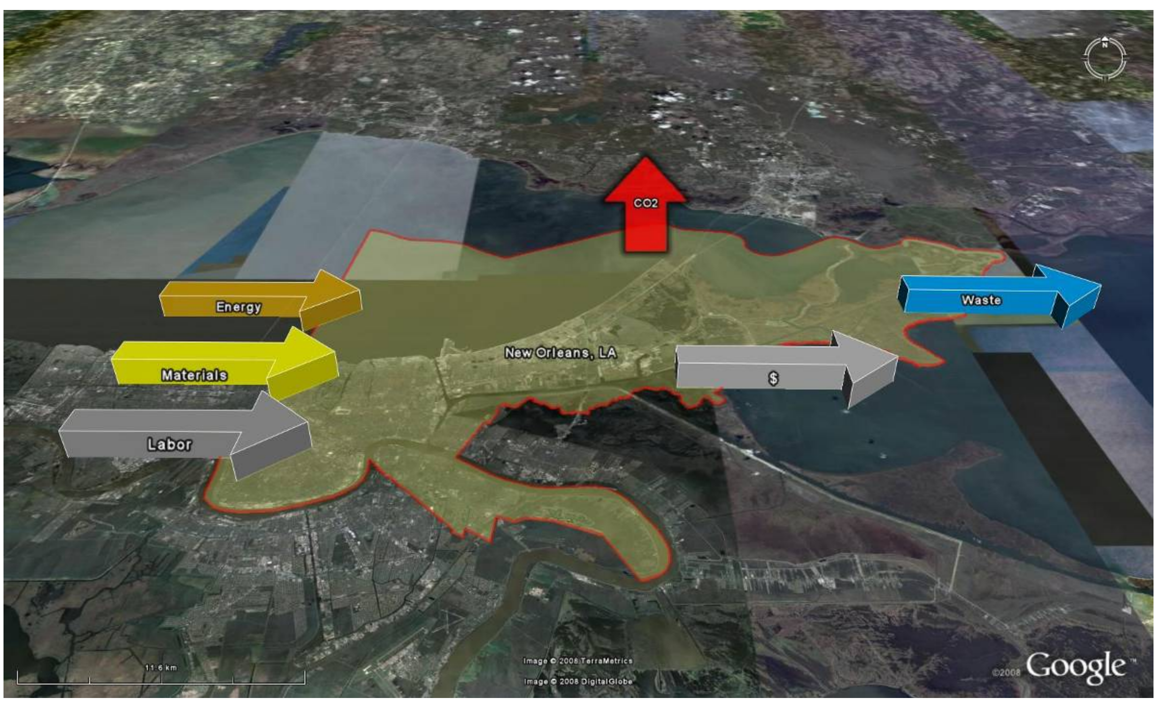

Figure 6: New Orleans Parish Boundary (data from ArcGIS displayed using Google Earth)

3.2 System Dynamics Model

The goal of this analysis was to examine the interactions between the resources required for houses in New Orleans and provide a way to compare different scenarios using an SD model. It was hoped that quantifying the effect of specific policies would make a stronger case for their implementation. This could be through improved regulations or building codes as an effort to promote 'greener' construction, the identification of specific retrofitting options for the existing housing stock, or the identification of financial incentives to encourage certain behaviors. It is also used to identify what tradeoffs are necessary to do this. The three phases of housing-life are defined in this study as 'Pre-Use' (construction of house), 'Use' (running of house), and 'Post-Use' (demolition or deconstruction at the end of the house's life). For each of these three phases, aspects of material, energy and labor were analyzed in detail. The analysis for each house type is discussed in greater detail in Chapter 4.

3.3 Stages of Analysis

The first stage of this analysis was to identify specific parts of the model that were dependant on external factors. This was achieved by analyzing a small portion of the city (Target Areas – discussed in Section 4.1) and using the data from these as a basis for calculating the construction material per house, energy consumption patterns and houses sizes. In this way, the effects with regard to material choice, energy consumption and labor are cleared and it is easier to understand what the results of a specific scenario are.

From this initial step, it became apparent that many of the interconnections were linear and that the behavior of this model was not leading to any unanticipated results. The model was dependant on exogenous variables and the structure of the model was similar to what was illustrated in Figure 2. So this model would more accurately represent the current state of the city, more emphasis was place on looking at the response of the city to the hurricane by considering how construction and demolition rates were influenced by the internal structure of the model, after the effect of the hurricane.

3.4 Driving Equation for a City

This macro-level of analysis started off with the premise that the city as a system has a driving force causing it to follow a certain pattern of behavior. This driving force is based on the collective human behavior proposed in Figure 7. This proposed behavior is illustrated with a reinforcing loop causing a city to function in a particular way. In reality, this model would have a balancing loop as a result of finite resources, which would prevent it growing exponentially. This model (Figure 7) assumes that human survival is a certainty and this driving force causes an anthropogenic system to revert to its equilibrium position once it has been disturbed. New Orleans is considered to be in equilibrium when the supply and demand of houses are within a certain tolerance, defined in this study as when the rate of new houses constructed is less than 0.5% of the total housing stock per year . This value is based on the historical rate of construction in New Orleans which was 600-700/year (0.27 – 0.32%) from 2000-2004 with a total housing stock of 219, 434 houses (US Census 2006b and US Census 2008). The pre-Katrina demolition rate was unknown, so the equilibrium is defined solely on construction.

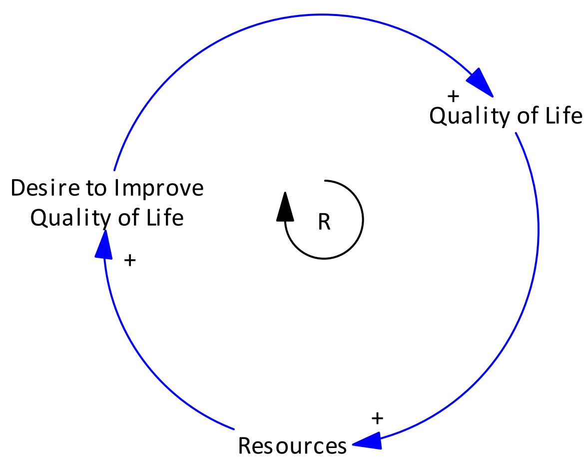

Figure 7: Proposed driving equation for resource consumption in relation to humans

Figure 8 is a representation of this 'driving force' specific to houses. The *Demand for Housing* is dependant on *Housing Stock* but there is a time-delay for the system to respond to a change in *Demand for Housing* (Figure 8). It is assumed that an increase in the level of wealth also results in a desire to improve housing quality.

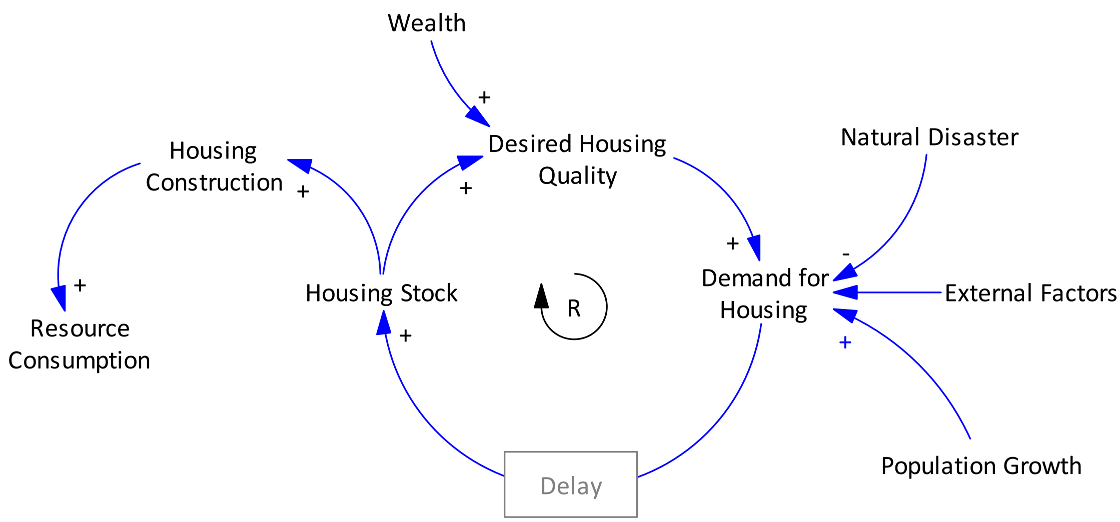

Figure 8: Driving equation in relation to housing

Figure 8 is a simple representation of the external forces driving the system. It does not consider the many specific urban characteristics of New Orleans. It is a city that is vulnerable to future environmental damage, as well as lacking resources with many complicated governance structures at local, state, and federal level. This combination of factors makes it difficult to predict any future trends with regard to external factors, such as population growth. However, there are advantages to viewing the city abstractly, in the form of an SD model with delays and response times. This approach enables estimates to be made with regard to how long it will take to return to equilibrium purely from a systems perspective.

3.5 Structure of System Dynamics Model

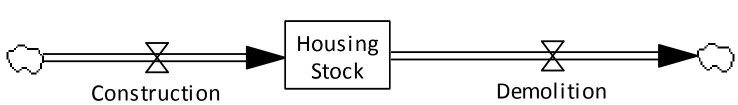

Figure 9: Illustration of Stock and Flow model

The concept of the stock and flow diagram in Figure 9 illustrates the methodology being used in this study. There is an inflow of houses due to *Construction* which contributes to *Housing Stock* and an outflow of houses in the flow named *Demolition* which decreases *Housing Stock.*

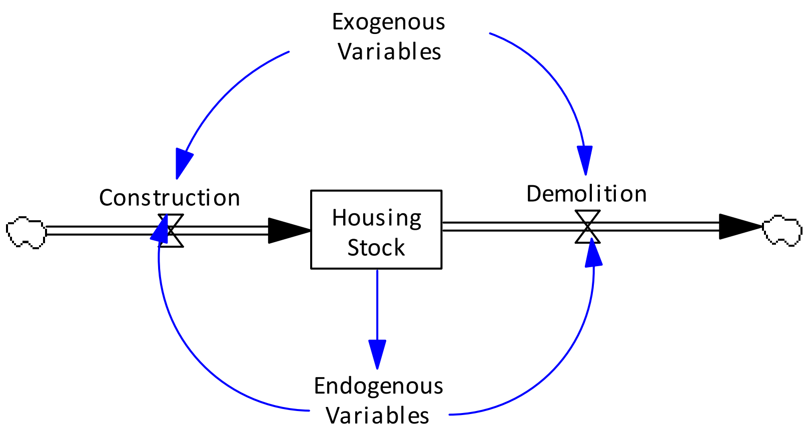

Figure 10: Exogenous and Endogenous variables

The rate of these inflows and outflows is determined by a combination of external and internal factors (alternatively described as exogenous and endogenous variables). Examples of exogenous variables that can influence these flows are economic growth, population, and catastrophic events (such as Hurricane Katrina). An example of an endogenous variable that can control a flow is the age of the housing stock. This requires a house to be replaced once it reaches the end of its life (assuming all other model parameters remain the same and the housing stock is set at a fixed level). In this model, flows relating to housing were examined using the primary unit of a 2000 sq ft house, which was the weighted-average value measured from data in Section 4.4.1.

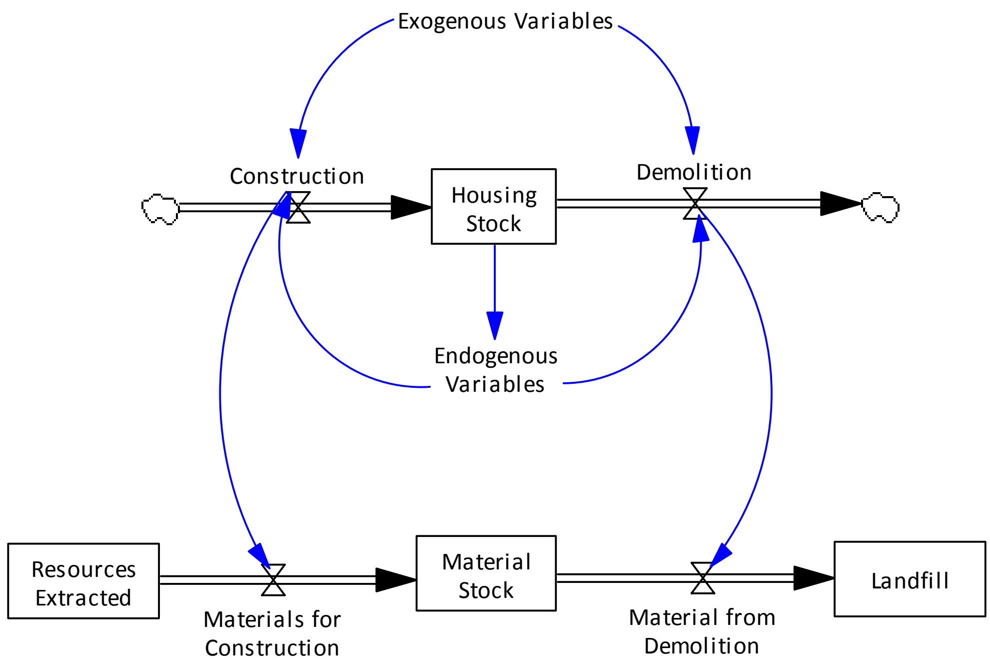

Figure 11: Simplified relationship between structure of housing model and materials

To examine the flows that relate materials, energy and labor, stocks and flows were constructed in parallel. The flow rates in each of these models were controlled by the 'Driving Equation' that represented the behavior of the housing stock. A simple version of the 'Driving Equation' is shown in Figure 9. Figure 11 and Figure 12 illustrate the concept of the parallel stocks and flows in relation to materials and energy. Within the structure of these parallel flows several feedback loops were proposed which influence the behavior of the overall system (including the primary model). These feedback loops are explained in greater detail in Sections 5.2-5.4.

Using SD to identify these feedback mechanisms is necessary, to develop a better understanding of what is occurring in the system being modeled. Defining this relationship is a necessary starting point so that the chain of causality can be verified. It is likely that estimating causal relationships in this way will require several iterations before they represent a part of a city sufficiently accurately. Relevant metrics will be required to validate this and confirm the causality of the relationship(s). This study is an initial step where certain patterns of behavior are proposed. Subsequently, the verification and refinement will come as a result of further work, discussion, and empirical validation.

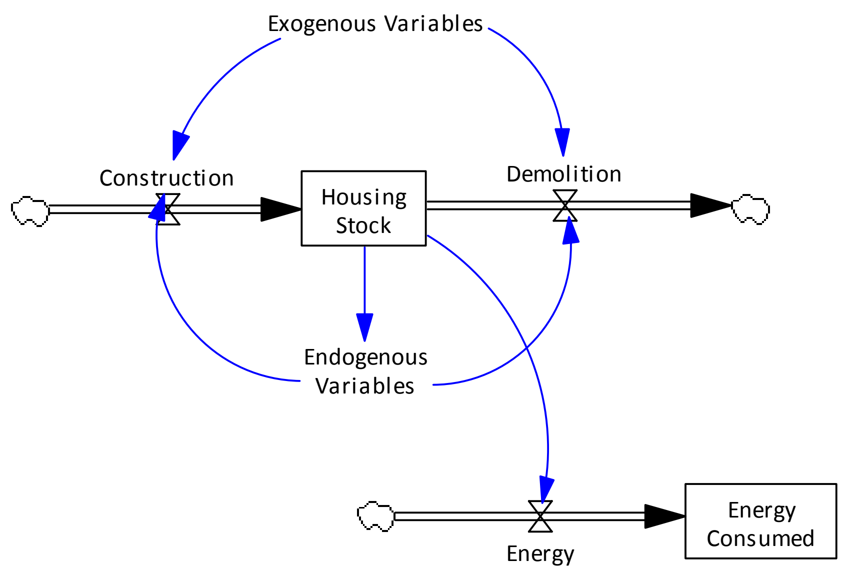

Figure 12: Relationship between housing stock and energy consumption during the 'Use Phase'

3.6 New Orleans as a System

Based on observation of the rate of reconstruction permits issued, it was noted that there are similar time-delay patterns that can be observed in standard SD models (see Appendix A.2.). From this observation, a model was proposed with a structure that would result in this pattern of behavior occurring.

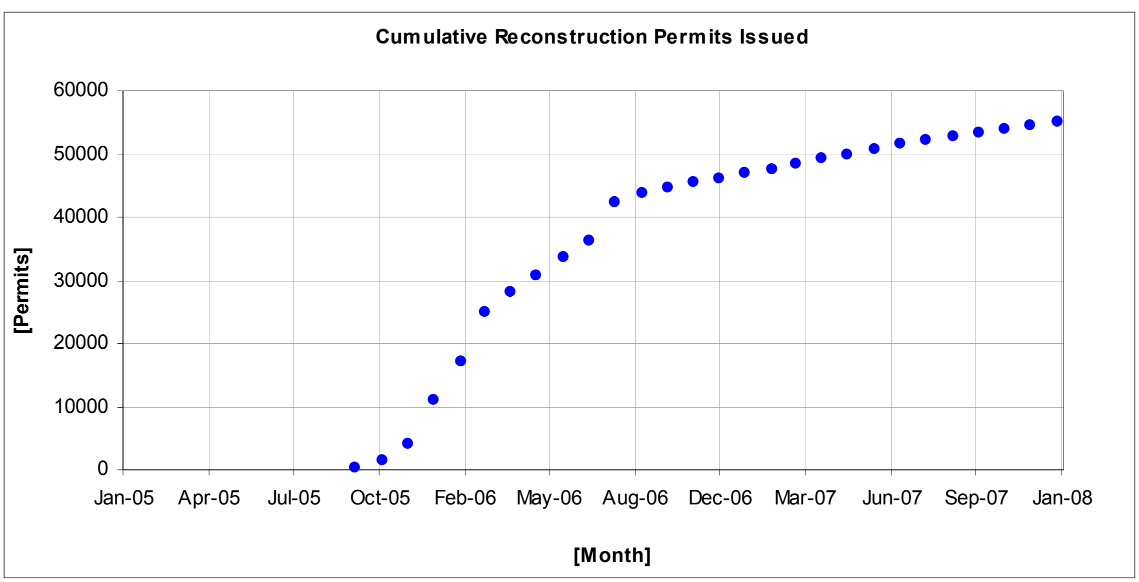

Figure 13: Cumulative Reconstruction Permits Issued (City of New Orleans, 2008)

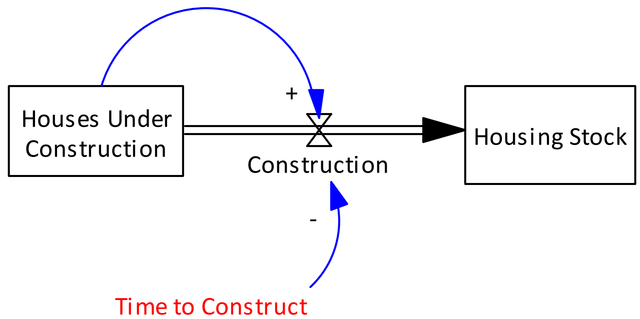

Figure 14: Time Delay (1st Order)

Figure 14 illustrates the behavior of a system with a time delay. The outflow of *Houses Under Construction* is proportional to the stock of material in transit and the contents of the stock are perfectly mixed at all times (Sterman 2000, 422). The equation for the flow is defined as *Houses Under Construction/Time to Construct*. This behavior is illustrated in Figure 15 and Figure 16.

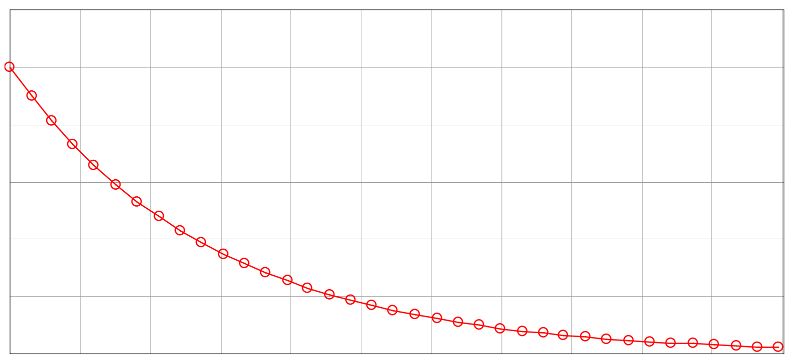

Figure 15: Exponentially decreasing stock (*Houses Under Construction*)

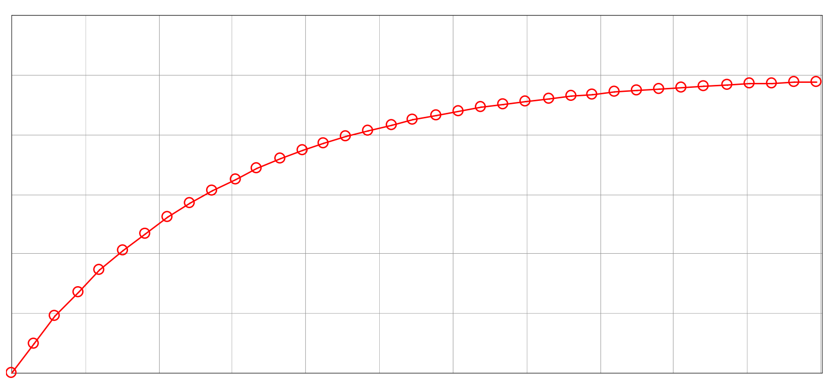

Figure 16: Change in *Housing Stock* over time

Interestingly, a similar pattern of behavior is suggested in the paper “Reconstruction of New Orleans after Hurricane Katrina: A research perspective” (Kates et al. 2006) but the reason (or data) for the shape of the curve is not given (Figure 17). This diagram is described as the “sequence and timing of reconstruction after Katrina in New Orleans with actual experience (solid lines) and sample indicators for the first year along a logarithmic time line of weeks after the disaster. The long-term projections (dashed lines) are based on an emergency period of 6 weeks, a restoration period of 45 weeks, and a 10-fold historical experience for reconstruction.” (Kates et al. 2006).

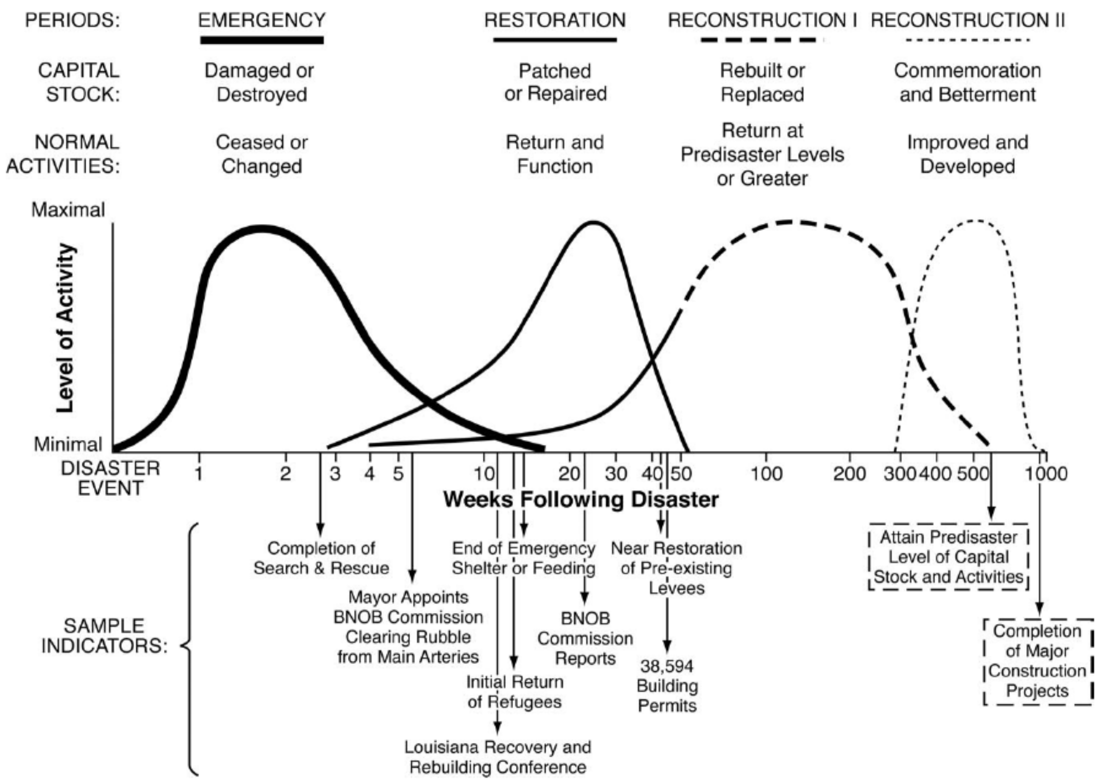

Figure 17: “The sequence and timing of reconstruction after Katrina in New Orleans.”
(Figure and text from Kates et al. 2006)

This pattern of behavior can be seen in Figure 18, which is a graph of the flow rate of houses from *Houses Under Construction* to *Housing Stock*. This flow rate is illustrated in Figure 19, and the model equations are listed in Appendix A.3. The positive slope of the curve is much steeper due to the pulsed demand caused by damage to 105,323 houses. To verify this pattern of behavior in New Orleans, permit-data (City of New Orleans), household and population data (US

Census data) and data that measured currently active households (Greater New Orleans Community Data Center) are compared with the theoretical model. These data enabled the theoretical model to be compared to the city at a macro-level. Theoretical data are used where there is an absence of information.

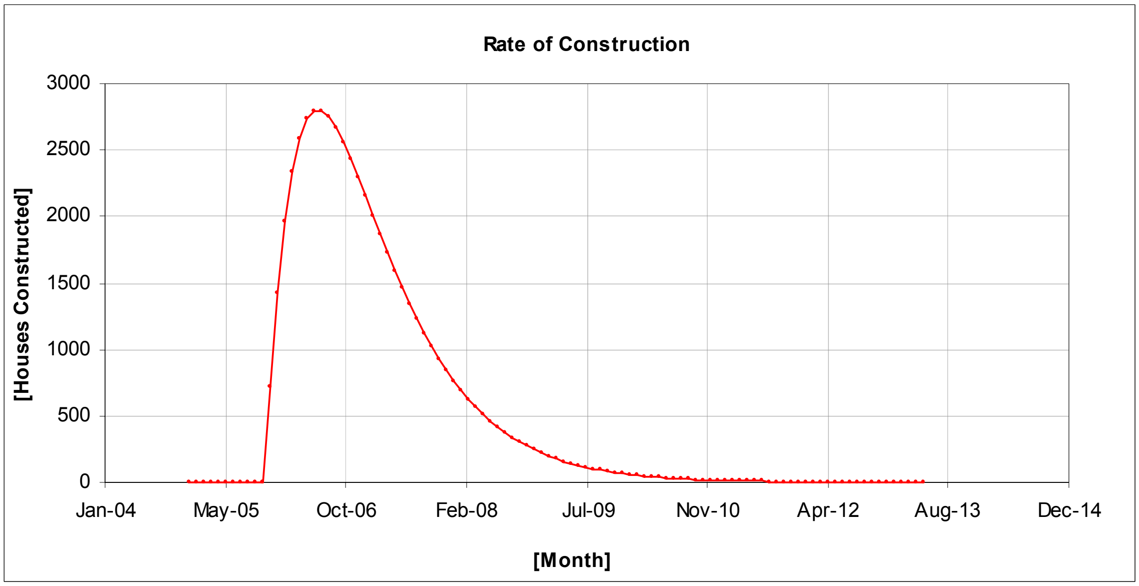

Figure 18: Projected rate of housing construction
(3rd Order Delay influencing the flow rate, from Figure 19)

The proposed model structure that relates permits, construction and delays is illustrated in Figure 19. The only user-defined variables that are required for this pattern to occur are *Time to Construct*, *Response Time of Residents* and *Time to process Permit* with values of 6.5, 10 and 2 months respectively. The effect of the hurricane is modeled as an outflow surge of 105,323 (FEMA[8] , 2005) at Time Step=8 (which corresponds to August, 2005). This is based on the damage estimates from FEMA (categorized as either 'Major Damage' or 'Severe Damage' for Orleans Parish).

There are similar patterns between the simulation and the data, but some of the specific technical reasons as to why these delays occur, have not been explored. This approach is primarily to illustrate that these patterns exist in a city (specifically in New Orleans) and with verification, could be used to predict future responses to natural disasters. In this case, a

[8] Federal Emergency Management Agency

retrospective analysis allows for the data to be used to validate the model. This type of simulation allows certain predictions to made in relation to the resources required for construction and as the number of houses is so great this has an impact on the national scale.

The initial estimates of the pre-Katrina housing stock are taken from the US Census which was undertaken in 2000 (US Census 2000b). The number of permits used to calculate Reconstruction (which is calculated based on permits from the following categories: Residential-Repair, Residential-Emergency, Residential-New and Residential-Refurbished) is graphed in Figure 20 (NOCH 2008). The fields 'Permit_Type' and 'Detailed_Permit_Type' were joined and the total number of permits for each category was tabulated using MS Access and MS Excel. These data were filtered from the total number of permits.

There are many factors which influence whether the homeowner uses the permit immediately. One major problem that affected many residents was a lack of funds due to delays in the bureaucratic system. However, over time it is reasonable to assume that the majority of the permits will be used for their intended purpose.

The model shown in Figure 19 assumed that there were two delays in relation to permits. The first delay was defined as *Response Time of Residents* and this was thought to be due to the rate of people returning to their homes and filing a permit for either reconstruction or demolition. The value for this variable was 10 months. The second delay was the *Time to process Permit* which was assumed to be a delay in the permit office of New Orleans for a permit to be processed so that the work could proceed. The value for this variable was 2 months.

The third delay in the system was defined as *Time to Construct* and was based on the length of time that it took for a house to be constructed. The value for this variable was 6.5 months. It was assumed that there was no delay in relation to the amount of time required to demolish a house. This is not entirely realistic, but there was no way of verifying the estimated time lag between a demolition permit being issued and the house being demolished.

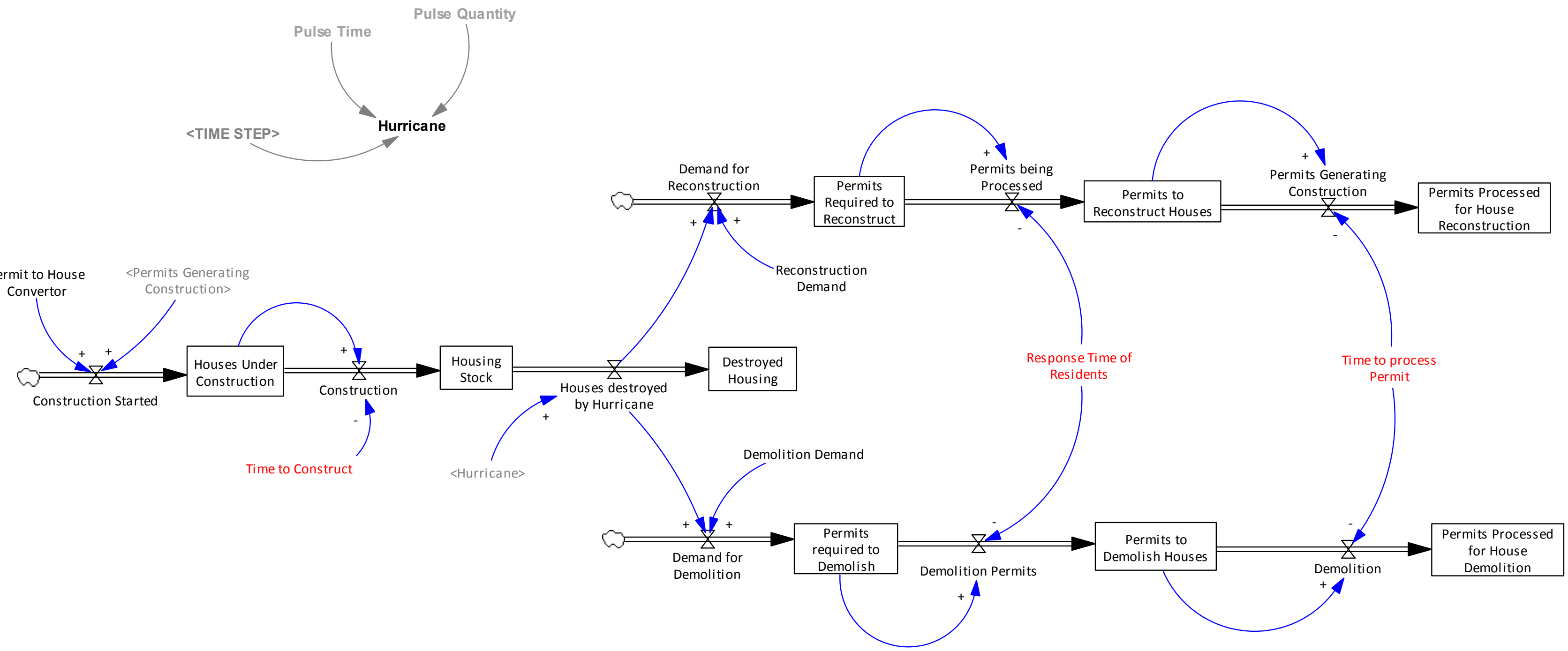

Figure 19: Model structure illustrating delays in relation to permits and construction

Variables:

Time to Construct:	6.5 months
Response Time of Residents:	10 months
Time to process Permit:	2 months

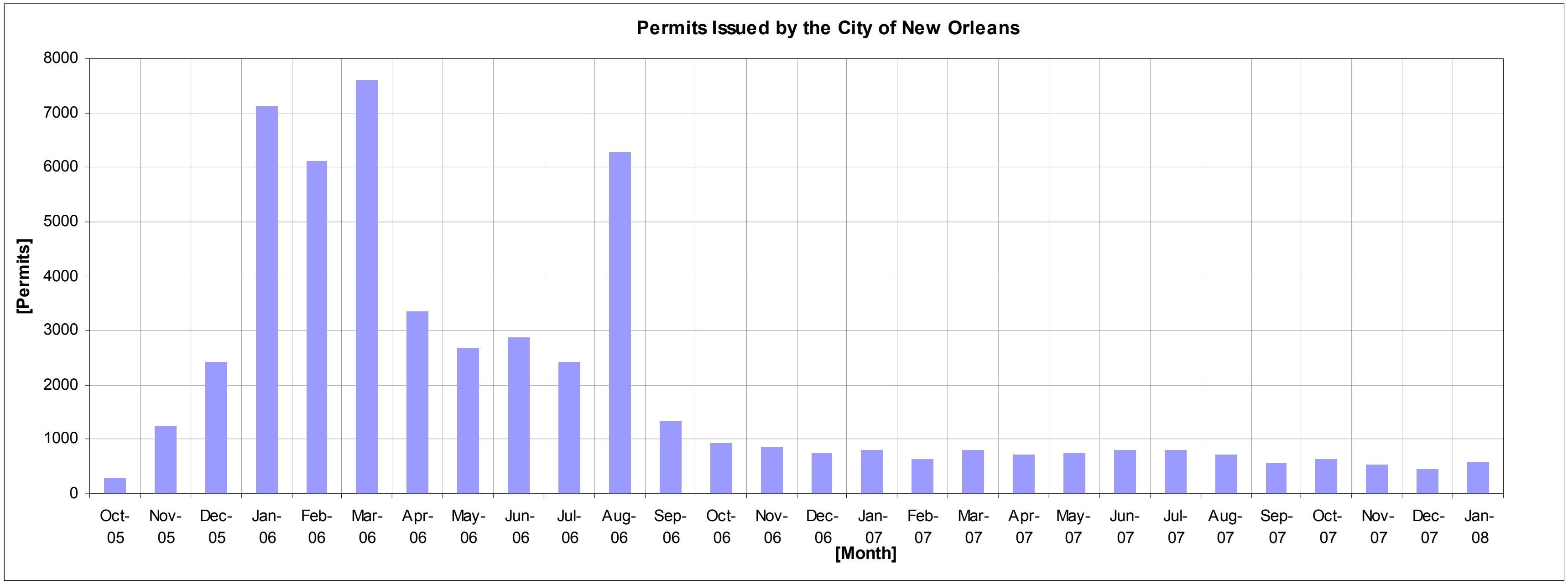

Figure 20: All permits issued by the City of New Orleans

3.7 Model Analysis

Based on the structure of the model and the three time delays identified (*Time to Construct*, *Response Time of Residents*, *Time to process Permit*), the simulation corresponds to the historic data quite closely (Figure 21, Figure 22, and Figure 23). The model was developed iteratively, considering where there might be delays in the system[9]. The values for the initial part of the model are slightly inaccurate (August 2006 is 15% greater than the historic value) but they appear to converge towards the same final value (from April 07 there is a difference less than 5% between the simulated and historic values). The coefficient of variation of the root mean square error (CVRMSE – see Appendix A.2) is 5.16% which is less than 15%[10]. For Figure 21, Figure 22, and Figure 23, the CVRMSE value was calculated for the portion of the model where historic and simulated data overlap after the hurricane occurs.

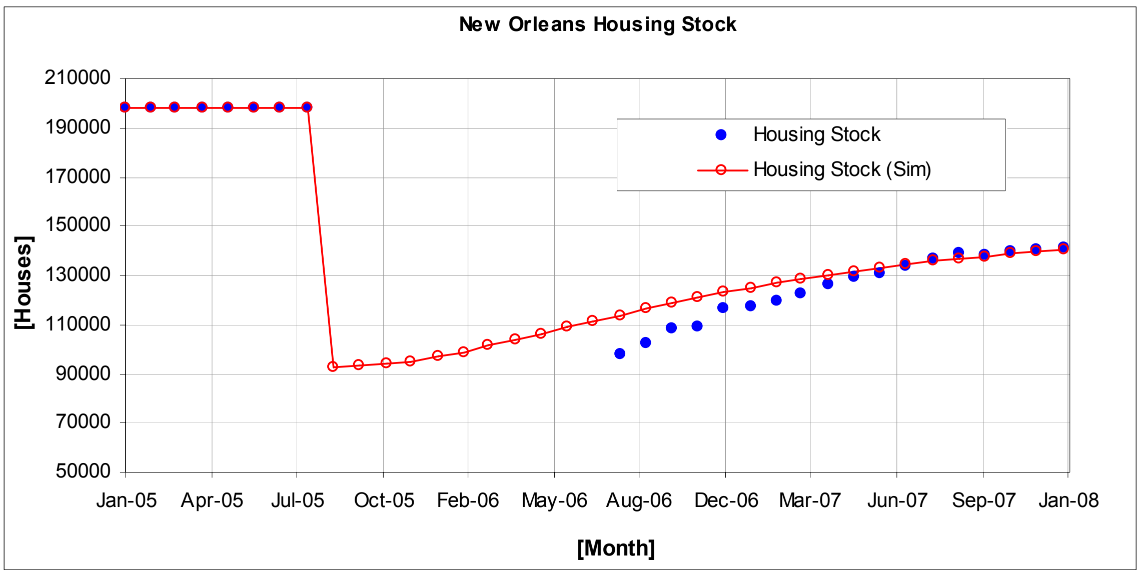

Figure 21: New Orleans Housing Stock

Figure 21 is a graph of the *Housing Stock* and is a result of three delays in the model matching two other time delays in the system; the *Response Time of Residents* and the *Time to process Permit.* Figure 22 illustrates the close match between the simulated and historic data with a CVRMSE=8.94%.

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[9] Prof. Paulo Goncalves had several useful suggestions for this part of the model.
[10] The recommended threshold value of the CVRMSE for models calibrated on a monthly basis is less than 15% (Ricker 2008 and Reddy 2006).

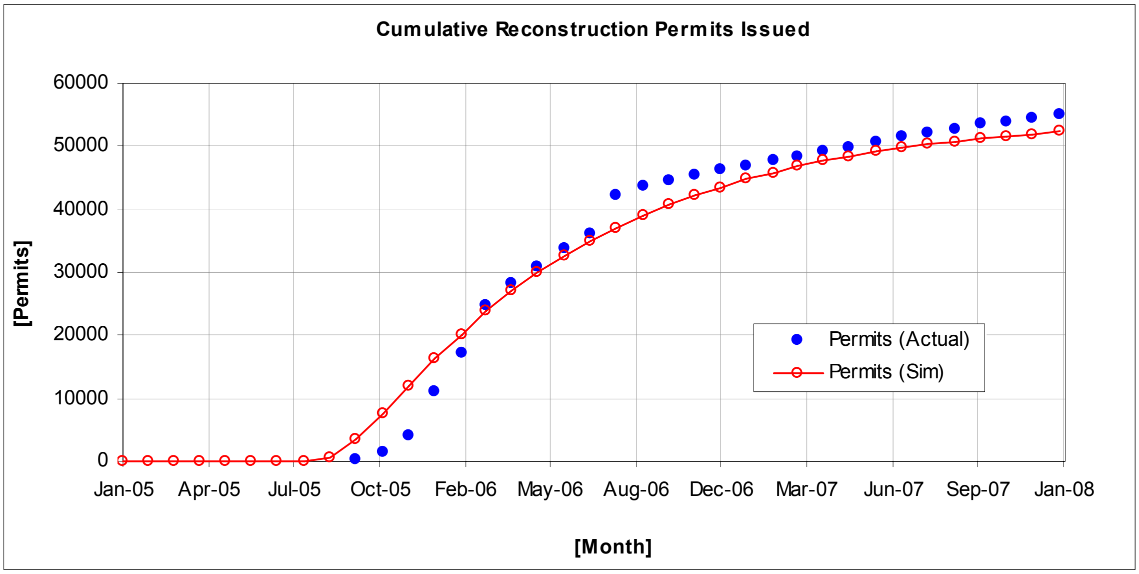

Figure 22: Cumulative Reconstruction Permits Issued

Figure 23 illustrates the simulated and actual data for the cumulative permits processed. The CVRMSE value is 16.28 % which is above the threshold of 15%. However, the simulated data appears to follow the general trend of the historic data so the simulation is still considered to approximate the behavior of the system. The same delay times were used for Figure 22 and Figure 23, yet there could be slight differences in the way that delays were caused in the system.

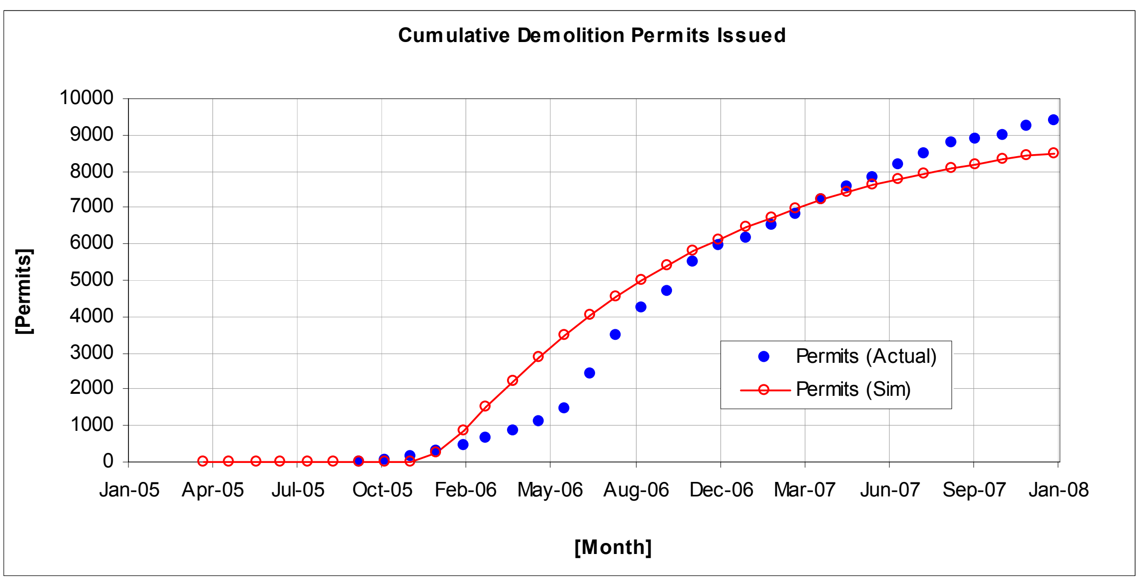

Figure 23: Cumulative Demolition Permits Issued

3.8 Effect on Employment in the Construction Sector

Due to the increased demand for housing, there is an increase in the employment in the construction sector as illustrated in Figure 24 (Bureau of Labor Statistics, 2007). This is a logical pattern of behavior, as an increased demand for houses requires more construction workers. An interesting aspect of this pattern is that there what appears to be a slight overshoot. This overshoot could possibly be caused by two time delays in the system which provides feedback regulating supply and demand.

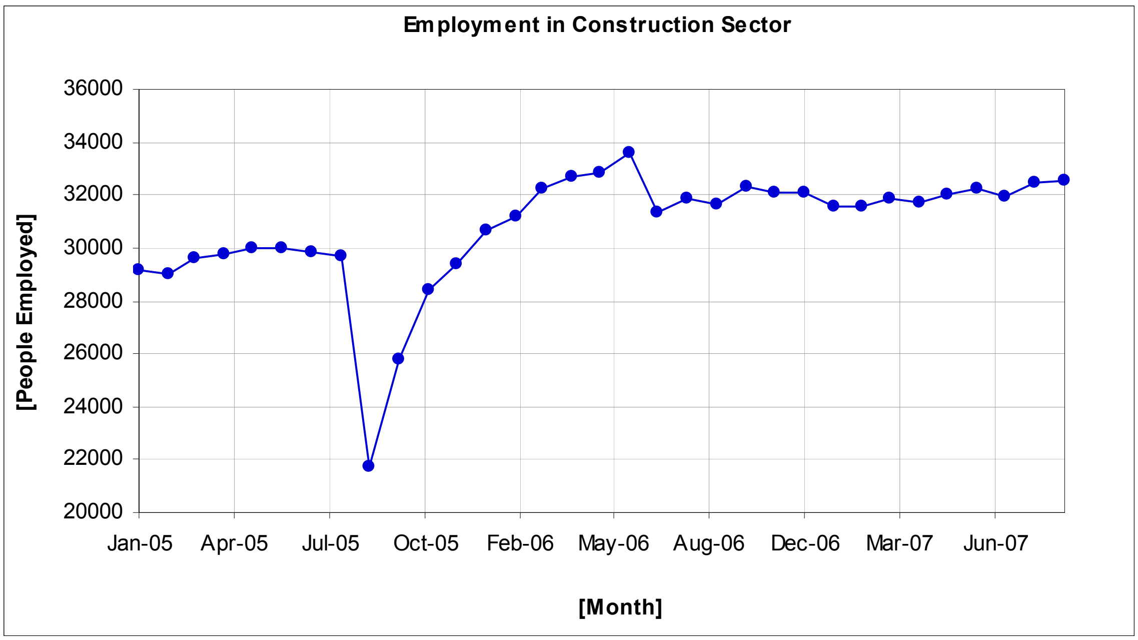

Figure 24: Number of people employed in construction sector (BLS 2008)

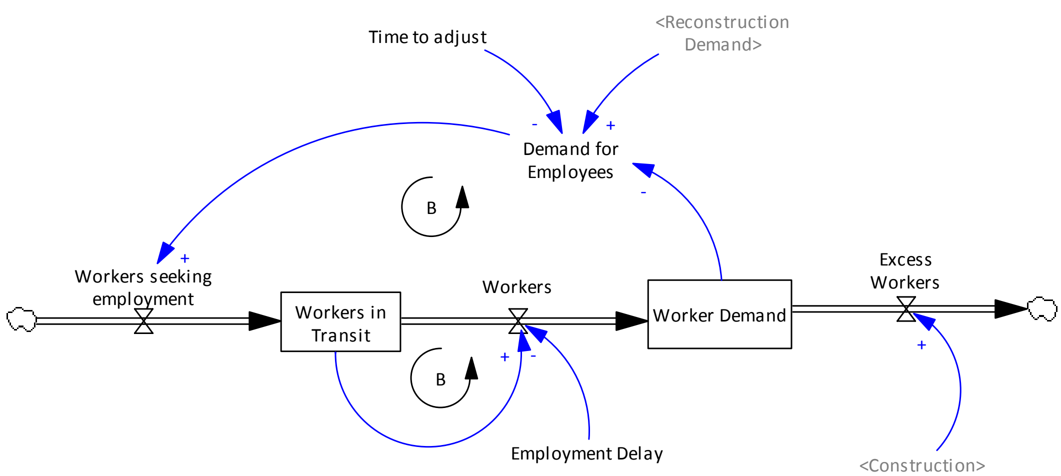

Figure 25: Employment as a result of housing demand

This pattern of behavior is explored in Figure 25. *Reconstruction Demand* and *Construction* are 'shadow variables'[11] that are defined in the model in Figure 19.

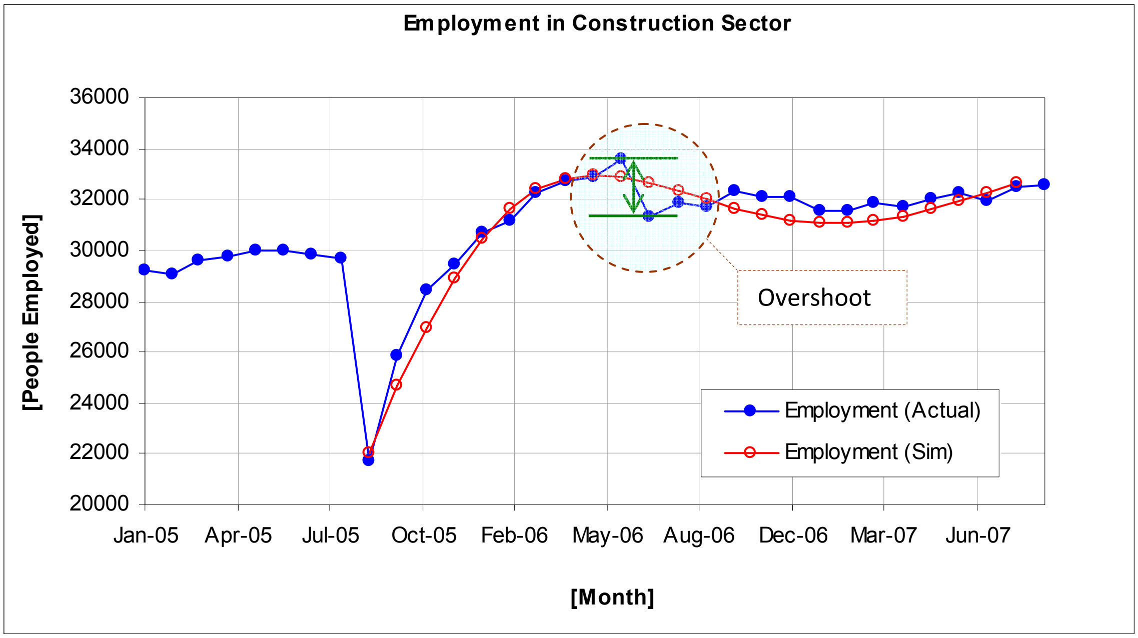

Figure 26: Overshoot in employment in construction due to time delays

The CVRMSE value is 2.14% for the simulated and historic data. The behavior of the simulated data is based on two delays within this part of the system, *Time to Adjust* (3.75 months) and *Employment Delay* (4.50 months) which leads to an overshoot (Figure 26) in terms of the response of the system. This would have resulted in an excess of workers being employed in the construction sector who would eventually lose their jobs as the system readjusted itself based on supply/demand feedback. The equations for this model are given in Appendix A.2.

3.9 Future Projections

This projection illustrated in Figure 27 assumes that all of the current conditions remain the same. The value that the housing stock starts to level off at is 147,326 (the Pre-Katrina level was 198,232). This is not an optimistic view of the situation and does not assume future growth, but merely that the system returns to the equilibrium situation based on the current number of permits that were applied for. According to this simulation, it reaches this equilibrium position at Aug 2009-Jul 2010 when the total number of houses constructed is less than 0.5% of the total

[11] A 'shadow variable' is a variable that is defined elsewhere in the model and referenced

housing stock. Inaccuracies between this projection and the actual situation may arise as not all homeowners may have applied for permits to do work on their house. It is possible that many did not apply for permits due to bureaucratic delays in the system.

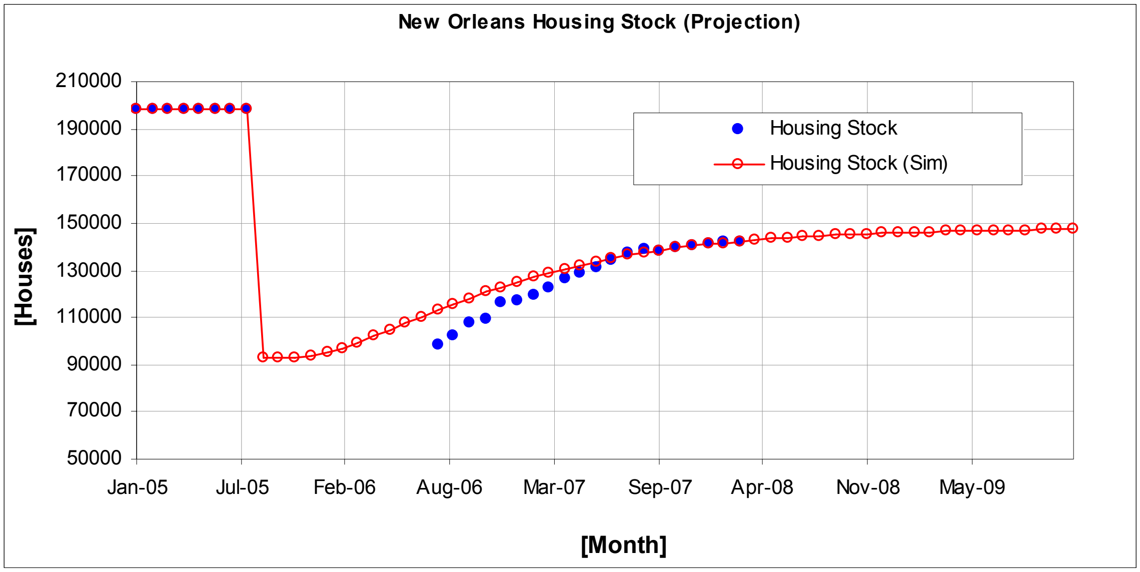

Figure 27: Future projected total housing stock (2005 – 2009)

3.10 Model Critique

Although this model does illustrate the behavior of the city of New Orleans as a SD system, it does not identify qualitatively what causes the delays, *Time to Construct*, *Response Time of Residents* and *Time to process Permit*. Not examining the causal factors limits the potential application of this model to other situations, but, it does recognize the importance of identifying these three time delays, and once identified, can provide an indication of how long it will take for this system to return to equilibrium. It is difficult to say with certainty that this model represents the response of New Orleans to Hurricane Katrina, as there could be additional factors that need to be included.

4 Methodology for Data Gathering and Analysis

This chapter describes the methods used to acquire data for this project. This aspect was challenging as many parameters had not been measured previously and some existing data had been destroyed or not updated since Hurricane Katrina.

Table 2: Details of resources which are analyzed

	Pre-Use	Use	Post-Use
Materials [kg]	Raw Materials Construction Refurbishment Waste	[-]	Demolition Deconstruction Waste
Energy [J]	Construction Transportation Direct Embodied	Running of house	Demolition Deconstruction
Labor [hr]	Construction Refurbishment	[-]	Demolition Deconstruction

Table 2 lists the resources that were examined. With regard to construction, New Orleans' data primarily consisted of survey data, permit data, typical construction details and labor details specific to the area. The methodology for gathering data is explained in this chapter and the details of the gathered data are presented in the following sections, with further details provided in Appendices B, C, D and E. For this study, there were several data sources that were used to estimate the usage of material, energy and labor which are referenced in the appropriate section.

4.1 Area of Analysis

The data which is used in this study were gathered from Target Areas (TAs). These are areas which have been designated by the City of New Orleans and the intention is to help these to develop so that they will revitalize the surrounding neighborhood. Limiting the data analysis to these areas was necessary due to the shortage of available data. Figure 28 shows the areas that were examined with regard to residential housing in New Orleans and identifies the boundary conditions of this study. Details of these areas are listed in Appendix B.1.

Figure 28: Target Areas used for gathering data (Google Earth and ArcGIS)

4.2 Challenges – Logistical and Political

As the city was recovering from a hurricane, it was difficult to gather data on many parameters; in addition some specific information had not been previously measured for the City of New Orleans. There were also legal difficulties accessing data from the gas and electricity utility provider (Entergy) as they had a commercial agreement with a private data-management company. Entergy would only allow data to be distributed that was not linked to a specific address, so general house typologies were identified based on building size; these house types were then assigned an average value based on the number of samples.

4.3 Data Gathering Approach

Based on the ORM's focus on Target Areas (TAs), it seemed logical to analyze these areas in detail as a first step of providing data that were relevant to the city and gathering useful data for this research. This was done by surveying all houses, generating building outlines and linking this information together. The TAs are not adjacent to each other (Figure 28), but the results of this data-gathering have been aggregated for all TAs.

4.4 General Housing Data

An estimate of building size was necessary so that the amount of material used during construction, the energy used during the service life of the building, and the labor used in construction, maintenance and demolition or deconstruction could be quantified. The age of the housing stock in New Orleans is illustrated in the following table (Table 3):

Table 3: House age (US Census 2000b)

Housing age	Orleans Parish
1999 - 2000	0.4%
1995 - 1998	1.3%
1990 - 1994	1.3%
1980 - 1989	8.2%
1970 - 1979	13.6%
1960 - 1969	15.1%
1950 - 1959	16.9%
1949 or earlier	43.2%

4.4.1 Estimating House Sizes

Generating building footprint outlines involved manually tracing high resolution aerial photographs (each pixel was equivalent to 6 inches) in a Geographic Information System (GIS) to approximate what these house outlines were. This was done using ArcGIS and 6 inch aerial orthophotographs from May 2006.

The polygons were manually traced using ArcGIS[12]. Figure 30 and Figure 31 are examples of a Target Area (Lower Ninth Ward - Figure 29) with building footprints traced. This was used to produce approximate building footprints for houses in the TAs, as no other building footprint records were available. This was a slow process which was used only to analyze the TAs.

[12] Polygons were traced mainly by Alice Brooks, and the author.

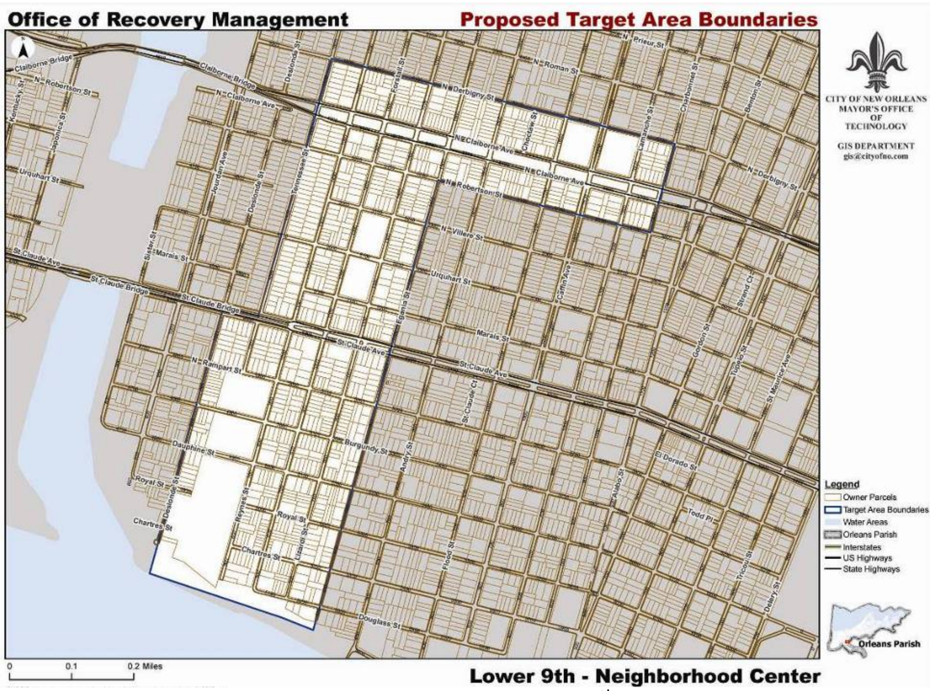

Figure 29: Target Area Boundary - Lower 9th Ward (ORM 2007)

Figure 30: Outline of Target Area using aerial imagery (USGS 2006)

Figure 31: Outline of house footprints using ArcGIS

The structure of a shapefile in ArcGIS is such that each polygon has attributes organized in a table associated with the polygon geometry as part of the file structure. This enables calculations to be repeated for each polygon automatically. These polygon outlines were combined with Light Detection and Ranging (LIDAR) data to estimate the building heights. These data were gathered from the United States Geological Service (USGS) and downloaded from Louisiana State University[13]. This is a remote sensing system used to collect topographic data (NOAA, 2008) with the data recorded in x,y,z point form. Raw (or first-return) data and bare-earth data were used in this study with the raw data providing the ground elevation, and the difference between the bare-earth and raw data giving the building heights. This average was calculated on the values of the points that fell within the polygon. LIDAR data were measured at an irregular point spacing of ~1.5m which was not close enough to use algorithms to automatically process them[14] so that buildings could be identified. As the orthophotographs had

[13] LIDAR: http://atlas.lsu.edu/lidar/ *U.S. Army Corps of Engineers, Saint Louis District, 2003*
Satellite Orthoimagery: http://seamless.usgs.gov/ *U.S. Geological Survey, 2006*

[14] Commercially available software from Leica Geosystems Geospatial Imaging was used to process this, but the point spacing was not close enough to distinguish buildings.

RGB color, rather than multi-spectral bands, this did not allow specific materials to be automatically identified, so it was not possible to automatically process them either.

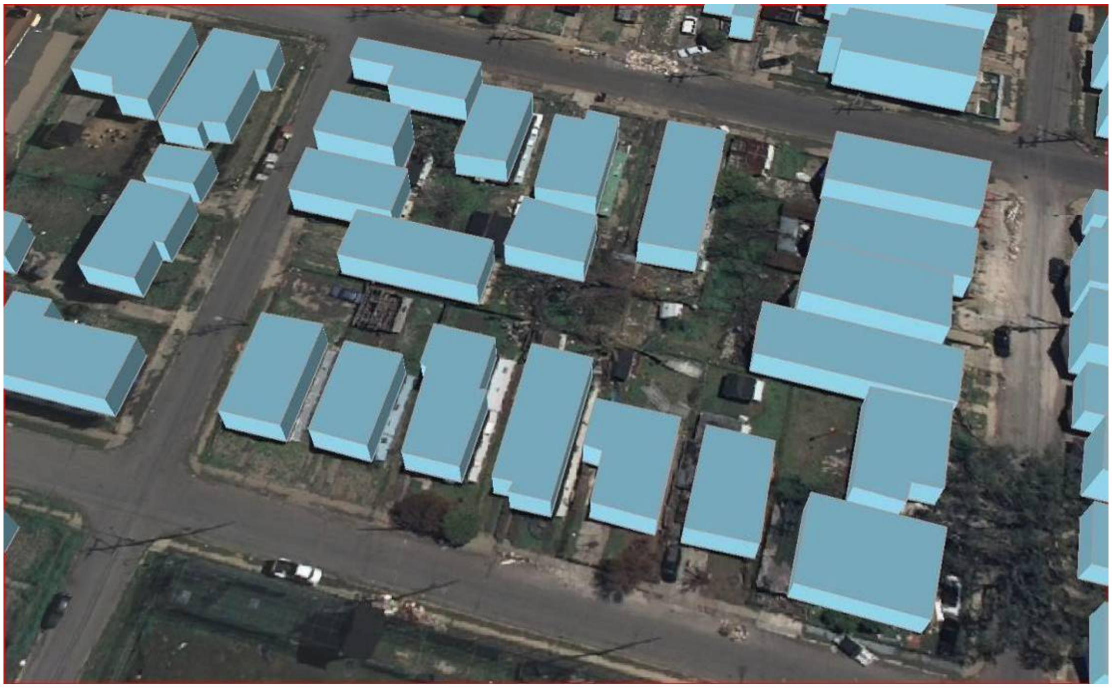

Figure 32: Building volumes generated in ArcScene

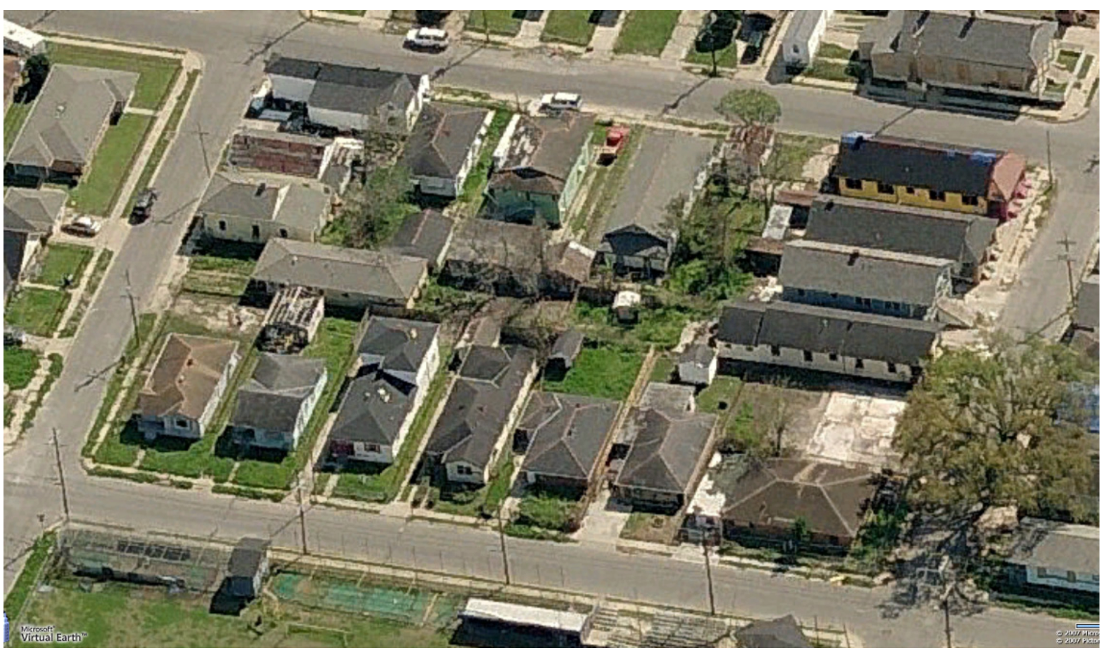

Figure 33: Stereographic imagery of **Figure 32** (http://www.microsoft.com/virtualearth/)

The Louisiana Pattern Book (Urban Design Associates, 2006) was used as a reference for typical floor to ceiling heights, typical roof pitches and typical window sizes (Table 4).

Table 4: Typical house heights

	One Storey	Two Storey
	[m]	[m]
Roof Vert	2.4	2.4
Floor Ceiling	2.9	5.8
Off ground	0.7	0.7
Total	6.0	8.9
Average height	4.8	7.7

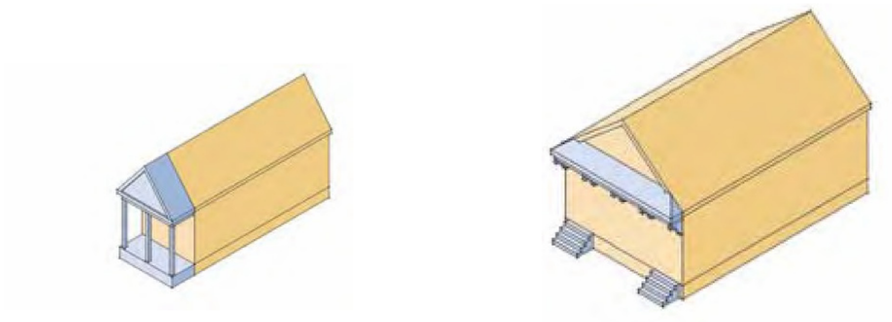

Figure 34: House sizes from the Louisiana Pattern Book (Urban Design Associates 2006)

The houses were grouped by area and volume into ten categories (Table 5). These categories were based on the plan area of the house, and the building heights. Eighty-five per cent of the houses which were derived from GIS data fitted into the categories in Table 5.

Table 5: House Categorization

House Type	House Area	Height	Width	Average Area	Length	Vol	Number	Percent
	[m2]	[m]	[m]	[m2]	[m]	[m3]	[#]	%
1	0-100	5	8	75	9	360	3766	11
2	101-150	5	8	125	15	600	195	19
3	151-200	5	8	175	21	840	158	19
4	201-250	5	8	225	27	1080	60	10
5	251-300	5	8	275	33	1320	117	9
6	0-100	8	8	75	9	577	3	2
7	101-150	8	8	125	15	961	9	7
8	151-200	8	8	175	21	1346	15	9
9	201-250	8	8	225	27	1730	27	6
10	251-300	8	8	275	33	2115	112	8

4.4.2 Target Area Survey Data

These data were gathered during summer 2006 as part of work by staff and students working in the ORM, including the author. More than 7,000 houses were surveyed and this information was collated with some of these results used in this study. The study consisted of collecting basic information about each individual house in seven of the TAs. Parameters recorded included:

- Condition of house (occupied or abandoned)
- Construction material used
- Refurbishment status (if house sustained damage)

The vast majority of houses surveyed were of wood stud construction. Initially the focus of this study was based on the TAs, however some of this information became less relevant following the decision to broaden the scope of the project to examine the entire city.

4.5 Construction Material Data

Construction materials were considered as existing in three phases, 'Pre-Use', 'Use' and 'Post-Use'. Section 4.5.1 – 4.5.3 discusses the material used in each phase.

4.5.1 'Pre-Use' Phase

To estimate what the typical materials are typically used in a one-story, New Orleans-style house, material take-offs were made from several architects plans for single family dwellings. Based on this data and densities for each material (Chudley and Greeno 2005), the mass per plan area was calculated for the floor, ceiling, roof and exterior wall. Several different houses were examined, and this data was then converted into an average value of material/sq area [kg/sq ft] that was used in the SD model. For example, the material 'convertor' that was used in the SD model to calculate the material required for the four housing systems is shown in Table 6. In the SD model, this value is called *Material_Convertor* and the units are in [kg/sq ft]. These values were stored in a 2D array (4 x 10) in the SD model.

Table 6: Material 'converter' values for construction

	Wood Stud	Steel Stud	AAC	SIP
	[kg/house]	[kg/house]	[kg/house]	[kg/house]
Lumber	12940	0	11578	10128
Concrete	22000	22000	22000	22000
Steel	0	1192	0	0
OSB	7242	7242	5227	8019
Gypsum	7398	7398	7398	7398
Asphalt	2215	2215	2215	2215
Vinyl	2169	2169	106	2169
Fiberglass	226	226	0	106
Building Paper	155	155	158	155
AAC	0	0	32233	0

Variable name: *Material_Convertor* [kg/house]

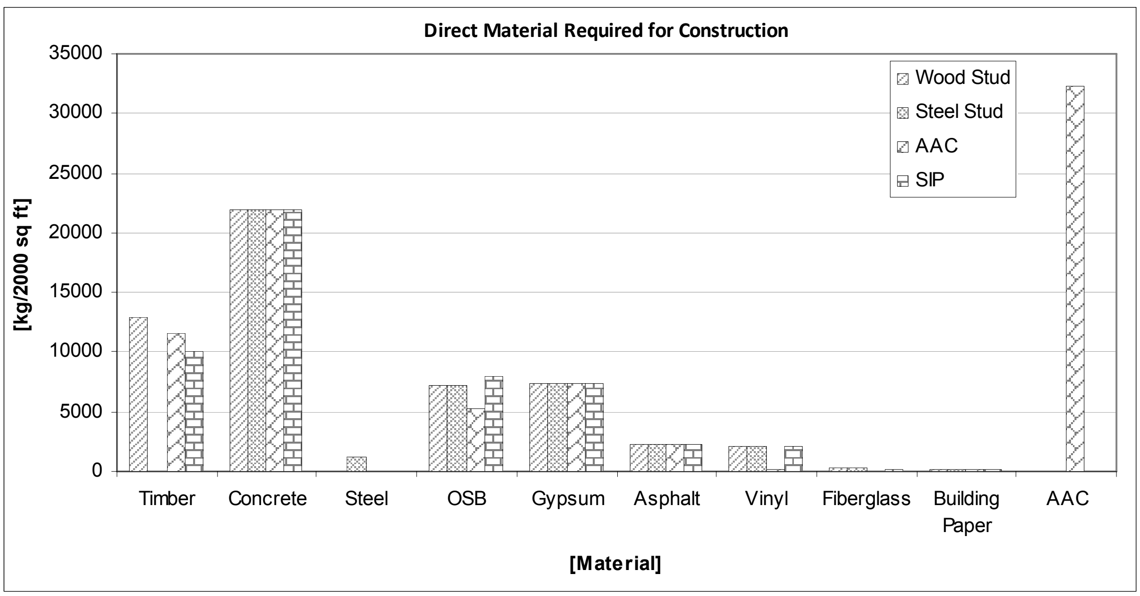

Figure 35: Material required for construction

The difference between the material required for construction and reconstruction was based on the assumption that the house being reconstructed did not need the structure to be rebuilt. For example, in a wood-stud house it was assumed that the studs could still be used. The material required for reconstruction is illustrated in Table 7 and Figure 36.

Table 7: Material 'converter' values for reconstruction

	Wood Stud	Steel Stud	AAC	SIP
	[kg/house]	[kg/house]	[kg/house]	[kg/house]
Lumber	0	0	0	0
Concrete	0	0	0	0
Steel	0	0	0	0
OSB	7242	7242	5227	8019
Gypsum	7398	7398	7398	7398
Asphalt	2215	2215	2215	2215
Vinyl	2169	2169	106	2169
Fiberglass	226	226	0	106
Building Paper	155	155	158	155
AAC	0	0	0	0

Variable name: *Material_Refurbish_Convertor* [kg/house]

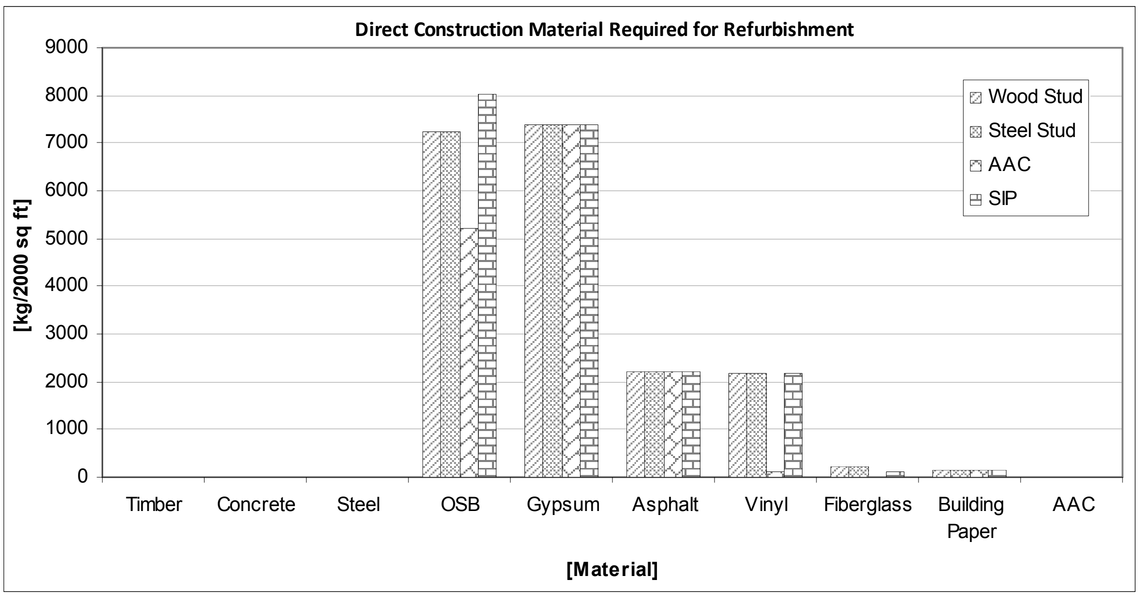

Figure 36: Material required for reconstruction

It was assumed that there was a waste fraction of 2 kg/sq ft for a wood stud house due to the construction process (EPA 1998) which equates to 4000 kg per house. This value is 0.074% of the total mass of material used during construction (the total material for a wood stud-house is 54 tons) and it was assumed that the percentage of waste for each construction process was the same.

Variable name: *Waste_Convertor* [kg/kg]

4.5.2 'Use' Phase

It was assumed that a negligible amount of material was consumed during the use phase. This is an assumption that could be refined once there is a way of incorporating the lifespan of materials into this model, rather than focusing only on building lifetimes. It was assumed that all materials used had the same lifespan as the building.

4.5.3 'Post-Use' Phase

This phase has two options, demolition or deconstruction. Estimates were made of the amount of material that can be recovered based on the material assembly. One average density of waste material that has been estimated is 1.5 ton/m^3 (Limbachiya 2004). Another value of 2.08 ton/m^3 has been calculated (US Army Corps of Engineers 1999). The amount of material recovered from each house was estimated to be of the following fraction for each material type (Table 8).

Table 8: Fraction of material recovered from deconstructed houses

Material	Fraction Recovered
Lumber	0.7
Concrete	1.0
Steel	1.0
OSB	0.0
Gypsum	0.5
Asphalt	0.3
Vinyl	0.0
Fiberglass	0.0
Build. Paper	0.0
AAC	1.0

Variable name: *Effectiveness* [MJ/kg]

4.6 Energy Data

The energy consumption for housing was considered over three phases, 'Pre-Use', 'Use' and 'Post-Use'. The majority of energy was consumed during the 'Use phase' (>90% of the total energy). Assumptions were made regarding the distance material was transported for construction and for either demolition of deconstruction.

4.6.1 'Pre-Use' Phase

The energy consumed during this phase consisted of the direct embodied energy (the material used to convert the raw resource into the finished product), the transportation energy and the energy required to build the structure. This data was not specific to New Orleans and was gathered from a variety of sources.

4.6.1.1 Direct Embodied Energy

The direct embodied energy is shown in Figure 37. These values are gathered from (Kibert 2005) and (Scheuer 2003).

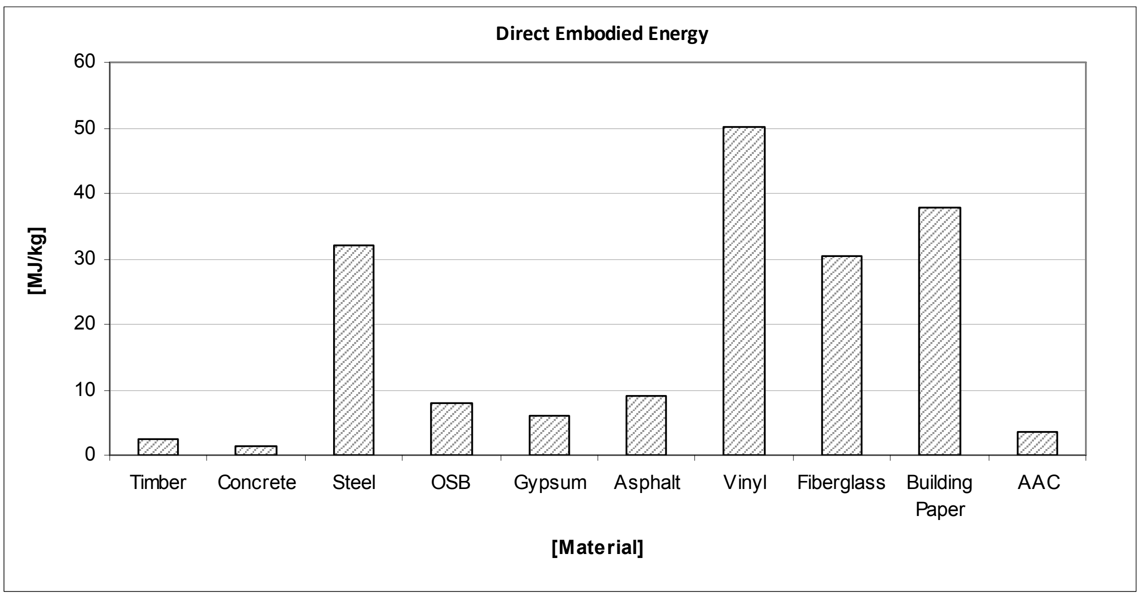

Figure 37: Direct embodied energy in materials examined

Variable name: *Direct_Embodied_Energy_Convertor* [MJ/kg]

4.6.1.2 Transportation and Construction Energy

Cole (1999) states that a "common assumption made in embodied energy analyses is that the construction portion is approximately 7-10% of total embodied energy". Cole illustrates that the construction energy and greenhouse gas emissions vary considerably from one structural system to another, with ranges from 2-25% of the total initial embodied energy. Some of the results from this study are shown in Figure 38. This study assumed an overall travel distance of 50 km, and based the labor hours and work rates on RS Means data (RS Means 2008). For the residential construction being considered in New Orleans, it is thought the amount of energy used for wood-stud, steel-stud, SIP, AAC would be comparable to the values shown for wood or steel (Figure 38). The value for concrete is higher as it takes into account the required formwork, cranes and concrete pumping-trucks which are not relevant in this study. There are little data available with regard to the energy required to construct various material assemblies. A value of 10 MJ/m^2 is assumed in this analysis for all on-site construction.

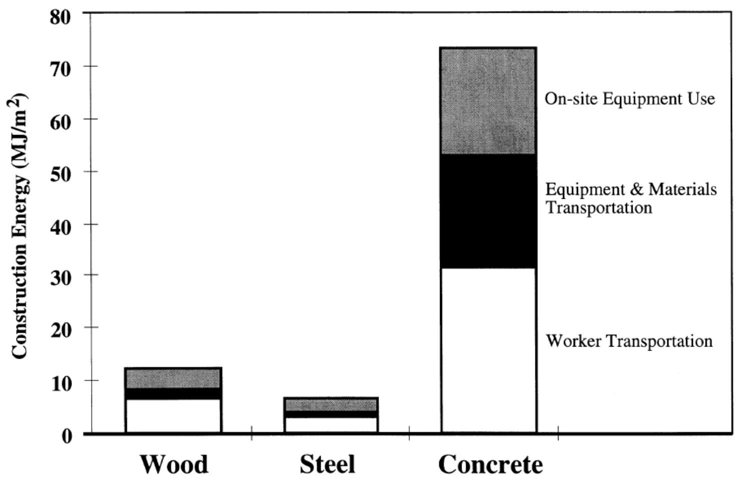

Figure 38: Construction energy required for various assemblies (Figure from Cole 1999)

Variable name: *Construction_and_Transportation_Energy_Convertor* [MJ/House]

4.6.2 'Use' Phase

The energy consumption of residential homes for heating and cooling was examined by analyzing data from a mixture of theoretical and actual data sources. Energy consumption simulations were done based on house size, three energy performance levels (which could depend on the type of construction) and typical occupancy patterns. These simulations were used to estimate what portion of energy was used to heat and cool houses and examine how it fluctuated on a month by month basis.

4.6.2.1 Theoretical Energy Consumption

Using eQuest (Version 3.60), simple models (Figure 39) were built of the ten different house types described in Table 5. eQuest is a free energy simulation software available from the US Department of Energy and uses the DOE2 energy simulation engine. The results shown in Table 9 are for three different energy performance levels of the 10 house categories. It is assumed each house conditions the air inside for both heating and cooling.

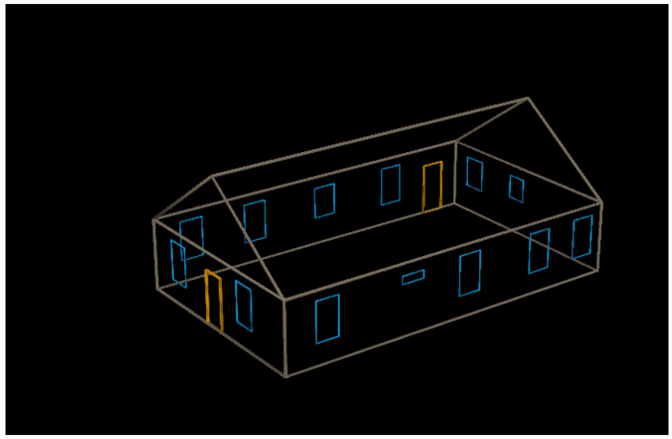

Figure 39: eQuest model of typical New Orleans house (wireframe model)

Gas was used as the heating fuel and electric air-conditioners were used for cooling. The air-conditioning units were auto-sized by eQuest, and all other efficiency measures used were left at the default values. This was assumed to be a reasonable decision, as these values are based on national household averages. The house was assumed to be south-facing; electricity was used for air-conditioning and gas for heating. The construction type examined was wood-stud, with ½ inch plasterboard on the inner walls. The results from this analysis are shown in Table 9.

Table 9: Annual Energy used for heating/cooling in New Orleans (eQuest simulation)

House Type	Infiltration	Insulation			Energy Consumption	Cooling	Heating		Total Heating + Cooling
		Wall	Roof	Floor		KWh	Btu	KWh	
	ACH	*HR-SQFT-F/BTU*				*x 000*	*x 000 000*	*x 000*	*KWh x 000*
1	0.3	R30	R30	R30	Low	4.69	9.57	2.8	7.5
	0.7	R13	R30	R4	Medium	4.89	18.83	5.5	10.4
	1.5	R4	R4	R4	High	5.37	25.81	7.6	12.9
2	0.3	R30	R30	R30	Low	6.20	10.08	3.0	9.2
	0.7	R13	R30	R4	Medium	6.69	25.5	7.5	14.2
	1.5	R4	R4	R4	High	7.51	36.57	10.7	18.2
3	0.3	R30	R30	R30	Low	8.70	11.81	3.5	12.2
	0.7	R13	R30	R4	Medium	9.31	33.12	9.7	19.0
	1.5	R4	R4	R4	High	10.42	47.75	14.0	24.4
4	0.3	R30	R30	R30	Low	11.23	13.53	4.0	15.2
	0.7	R13	R30	R4	Medium	11.98	40.64	11.9	23.9
	1.5	R4	R4	R4	High	13.36	58.84	17.2	30.6
5	0.3	R30	R30	R30	Low	12.67	14.35	4.2	16.9
	0.7	R13	R30	R4	Medium	13.72	47.36	13.9	27.6
	1.5	R4	R4	R4	High	15.46	69.65	20.4	35.9
6	0.3	R30	R30	R30	Low	10.11	9.57	2.8	12.9
	0.7	R13	R30	R4	Medium	10.53	20.84	6.1	16.6
	1.5	R4	R4	R4	High	12.09	36.8	10.8	22.9
7	0.3	R30	R30	R30	Low	14.02	10.7	3.1	17.2
	0.7	R13	R30	R4	Medium	14.79	28.26	8.3	23.1
	1.5	R4	R4	R4	High	17.20	51.56	15.1	32.3
8	0.3	R30	R30	R30	Low	18.94	12.49	3.7	22.6
	0.7	R13	R30	R4	Medium	19.96	36.3	10.6	30.6
	1.5	R4	R4	R4	High	23.18	66.59	19.5	42.7
9	0.3	R30	R30	R30	Low	24.21	14.5	4.2	28.5
	0.7	R13	R30	R4	Medium	25.55	44.43	13.0	38.6
	1.5	R4	R4	R4	High	29.53	81.64	23.9	53.5
10	0.3	R30	R30	R30	Low	28.04	15.87	4.6	32.7
	0.7	R13	R30	R4	Medium	29.79	51.94	15.2	45.0
	1.5	R4	R4	R4	High	34.65	96.49	28.3	62.9

Because this analysis has inherent uncertainty, and there area a large number of house-specific values required, BEopt (Building Energy Optimization) was considered to be a more appropriate type of simulation software for estimating the range of energy in New Orleans houses. BEopt (Version 0.8.5 Beta) is a free energy simulation software available from the US Department of Energy and uses the DOE2 simulation engine. Although it was more difficult to specify the aspect ratio of houses (as defined in Table 5) as accurately, the same square footage, floor to ceiling height and roof slope was used for analysis, while considering various levels of energy performance. In addition, BEopt allows parametric analysis and can calculate what cost/benefit retrofit options are most beneficial. Figure 40 illustrates a sample rendering of a house form generated through BEopt (the eQuest rendering engine is used). Unlike eQuest there is not as much freedom to position or size windows. As before, the house was assumed to be south-facing, electricity was used for air-conditioning and gas for heating.

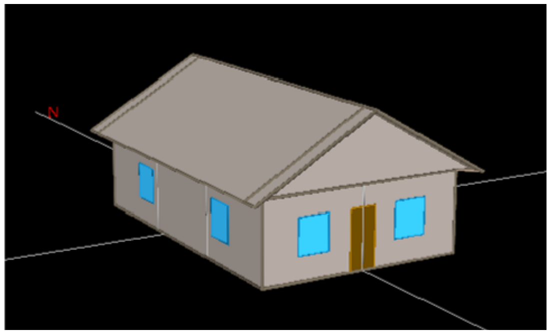

Figure 40: eQuest render of house generated using BEopt (House Category 1)

It was assumed for this analysis that there were adjacent houses at 10ft. This is a reasonable estimate as houses are positioned very close to each other in New Orleans.

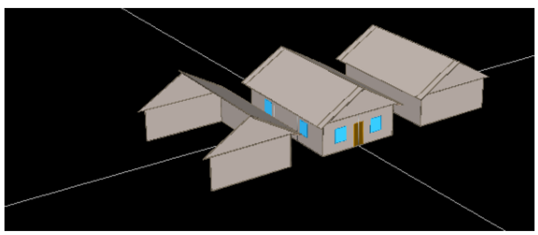

Figure 41: eQuest render illustrating neighboring houses at 10 ft

The R-values for the wall, roof and floor are slightly different than those used in Table 9 as BEopt has predefined values for a range of these parameters. It is not possible to change these values. In addition, one other difference with regard to air infiltration was due to BEopt defaults (BEopt uses the 'specific leakage area' and the previous analysis in eQuest used the 'effective leakage area'). The 'effective leakage area' can be selected to represent different construction methods or additional weatherproofing. The 'specific leakage area' is defined as the total effective leakage area of the space divided by the finished floor area.

Figure 42, Figure 43, Figure 44 and Figure 45 illustrate the results of the BEopt analysis for House Type 1. The data for all house types are summarized in Table 10 and illustrated graphically in Figure 46. Appendix D.1 shows the theoretical analysis combined with the historical energy consumption values.

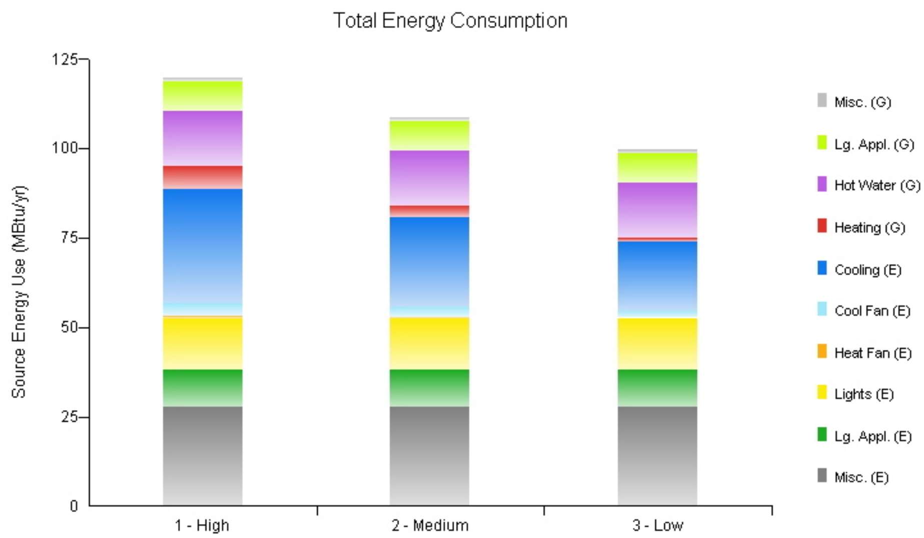

Figure 42: Annual Energy Consumption for House Type 1

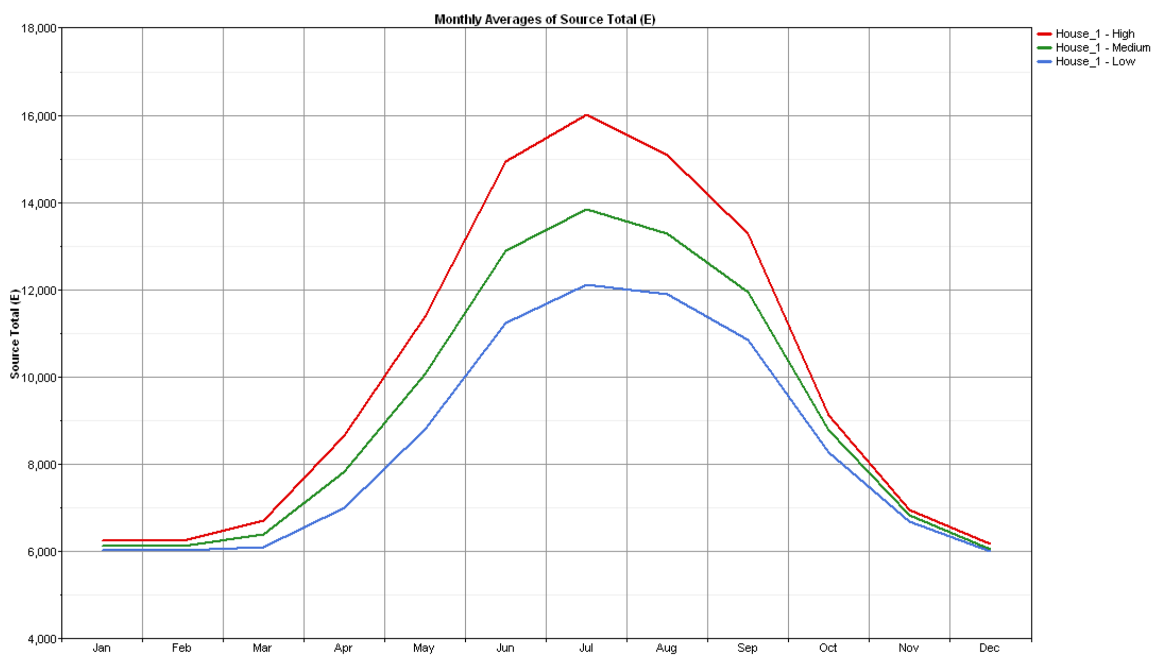

Figure 43: Monthly rate of energy consumption of electricity for House Type 1 [kW/month]

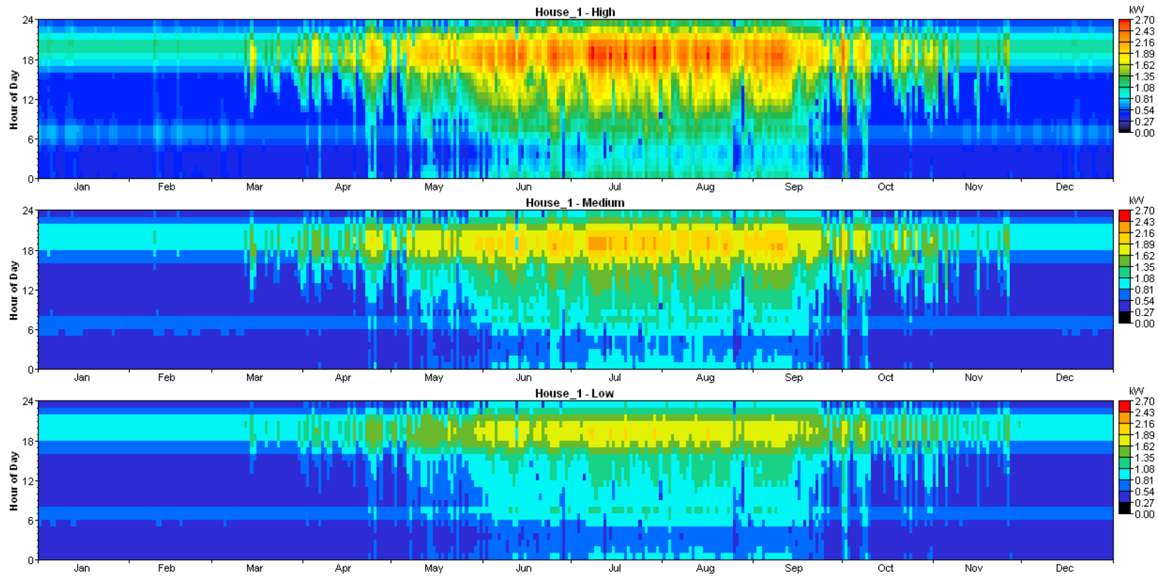

Figure 44: Annual electricity consumption for House Type 1 [kW per hour]

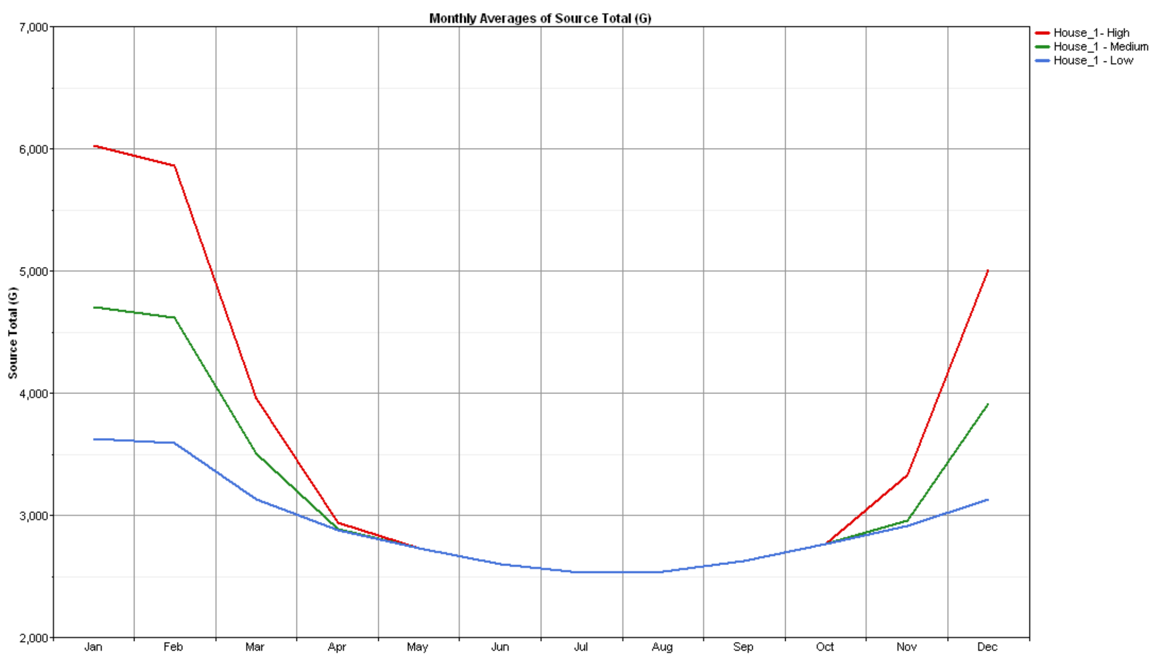

Figure 45: Monthly rate of energy consumption of gas for House Type 1 [MBtu/month]

For consistency, the units in Table 10 have been converted from MBtu to kWh from (1 MBtu = 293.1 kWh) so they can be compared to Table 9.

Table 10: Annual energy usage for heating/cooling in New Orleans (BEopt simulation)

House Type	Infiltration SLA	Insulation Wall	Insulation Roof HR-SQFT-F/BTU	Insulation Floor	Energy Consumption	Cooling KWh x 000	Heating KWh x 000	Total Heating + Cooling KWh x 000	Total Energy KWh x 000
1	0.00080	R27.5	R49.48	R30	Low	5.64	0.24	5.88	29.15
	0.00015	R15.3	R39.48	R11	Medium	7.33	0.96	8.29	31.84
	0.00050	R8.2	R29.48	R4	High	9.30	1.91	11.22	35.07
2	0.00080	R27.5	R49.48	R30	Low	6.36	0.81	7.17	32.63
	0.00015	R15.3	R39.48	R11	Medium	9.25	2.21	11.47	37.39
	0.00050	R8.2	R29.48	R4	High	12.17	4.07	16.24	42.66
3	0.00080	R27.5	R49.48	R30	Low	7.34	1.55	8.9	36.6
	0.00015	R15.3	R39.48	R11	Medium	11.34	3.53	14.9	43.2
	0.00050	R8.2	R29.48	R4	High	15.11	6.31	21.4	50.4
4	0.00080	R27.5	R49.48	R30	Low	8.47	2.39	10.9	40.8
	0.00015	R15.3	R39.48	R11	Medium	13.55	4.81	18.4	49.1
	0.00050	R8.2	R29.48	R4	High	18.09	8.49	26.6	58.1
5	0.00080	R27.5	R49.48	R30	Low	9.67	3.29	13.0	45.2
	0.00015	R15.3	R39.48	R11	Medium	15.84	6.19	22.0	55.2
	0.00050	R8.2	R29.48	R4	High	21.11	10.67	31.8	66.0
6	0.00080	R27.5	R49.48	R30	Low	5.88	0.24	6.1	29.4
	0.00015	R15.3	R39.48	R11	Medium	7.31	1.26	8.6	32.2
	0.00050	R8.2	R29.48	R4	High	8.80	2.81	11.6	35.5
7	0.00080	R27.5	R49.48	R30	Low	6.71	0.78	7.5	33.0
	0.00015	R15.3	R39.48	R11	Medium	9.30	2.57	11.9	37.9
	0.00050	R8.2	R29.48	R4	High	11.65	5.26	16.9	43.5
8	0.00080	R27.5	R49.48	R30	Low	7.70	1.46	9.2	36.9
	0.00015	R15.3	R39.48	R11	Medium	11.32	3.98	15.3	43.8
	0.00050	R8.2	R29.48	R4	High	14.42	7.71	22.1	51.3
9	0.00080	R27.5	R49.48	R30	Low	8.76	2.27	11.0	41.1
	0.00015	R15.3	R39.48	R11	Medium	13.36	5.44	18.8	49.7
	0.00050	R8.2	R29.48	R4	High	17.17	10.19	27.4	59.1
10	0.00080	R27.5	R49.48	R30	Low	9.90	3.17	13.1	45.3
	0.00015	R15.3	R39.48	R11	Medium	15.46	6.91	22.4	55.7
	0.00050	R8.2	R29.48	R4	High	19.93	12.68	32.6	67.0

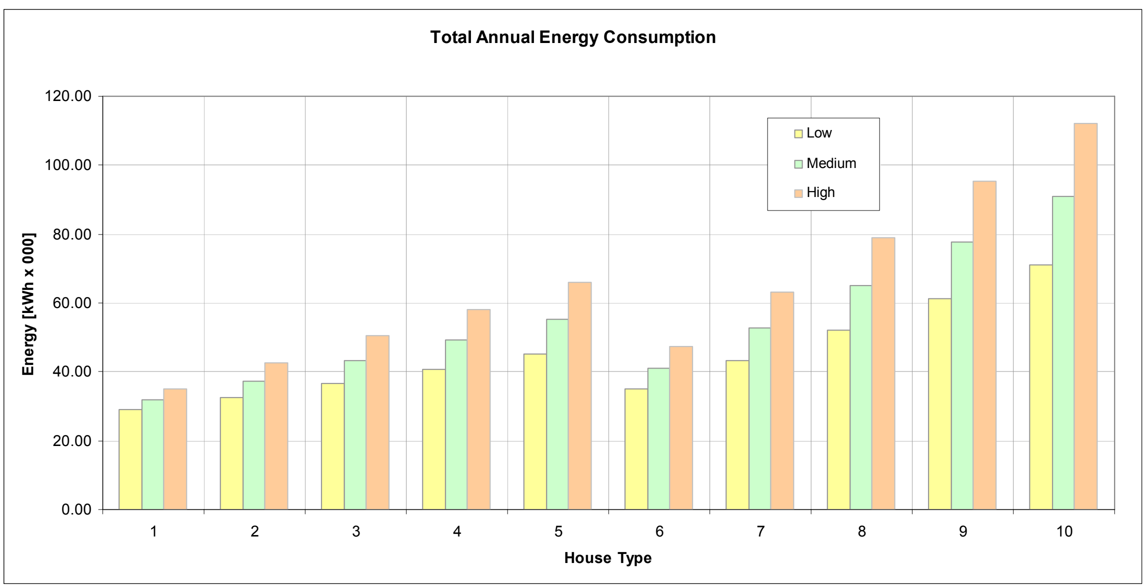

Figure 46: Total energy consumption for various house types [kWh x 000]

4.6.2.2 Critique of simulation

One assumption that was made, which may need to be revised, was that single and double shotgun houses were not analyzed differently with regard to energy consumption. As a house could either contain one or two families, and each family would have a minimum fixed level of energy consumption for domestic appliances, this would lead to inaccuracies. In addition, the effect of various construction materials and their impact on thermal mass was not considered in either analysis.

4.6.2.3 Actual Energy Consumption

Once the polygons were categorized into house types, this information was combined with the New Orleans City housing database by the GIS department in City Hall which linked the attribute table on the shape-file to the housing database. With this housing address, the historic energy consumption could be extracted from the Entergy customer database.

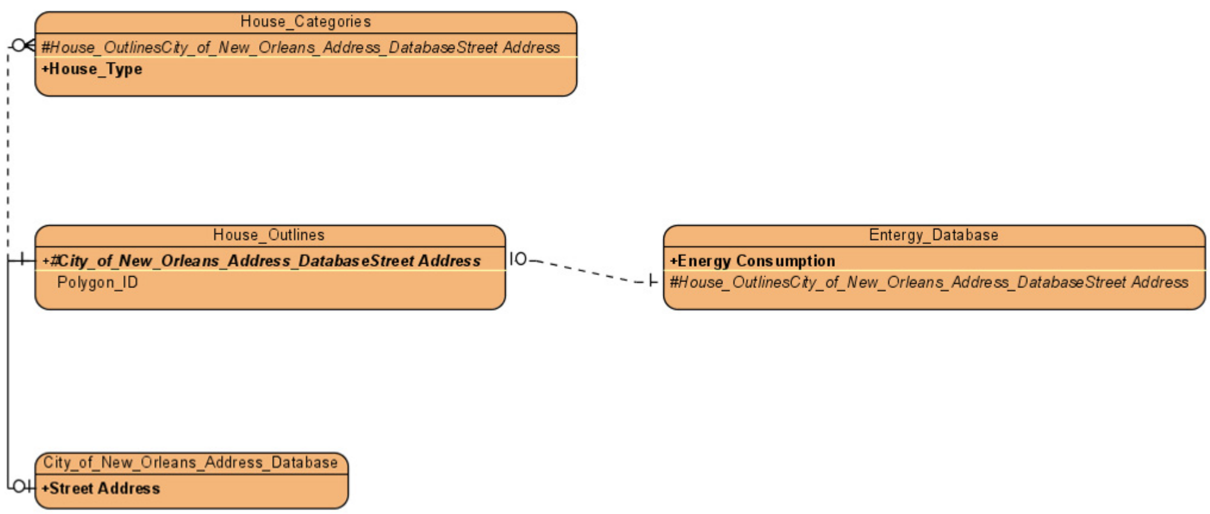

Figure 47: Database inter-linkages

This database was submitted to GCR who provided utility meter-data for each address, on a monthly basis. Due to privacy concerns, the exact address and data were not provided, however data for every meter for each address were extracted. This utility consumption was compared with the theoretical models so that an estimate of the heating/cooling energy consumption could be identified. To try and identify anomalies in the data, certain values were screened out based on the identification of a reasonable range.

4.6.2.4 Actual Energy Consumption

The theoretical and actual energy consumption is shown for House Type 3 in Figure 48 and Figure 49. The analyses of all ten houses is shown in Appendix D.1

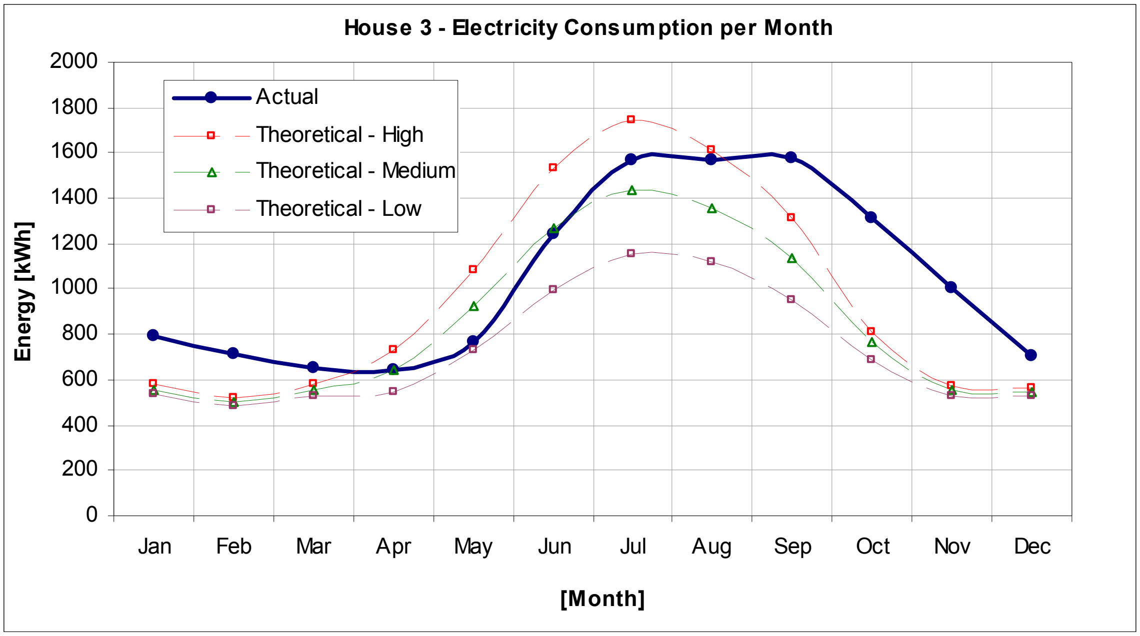

Figure 48: House 3 – Monthly Electricity Consumption

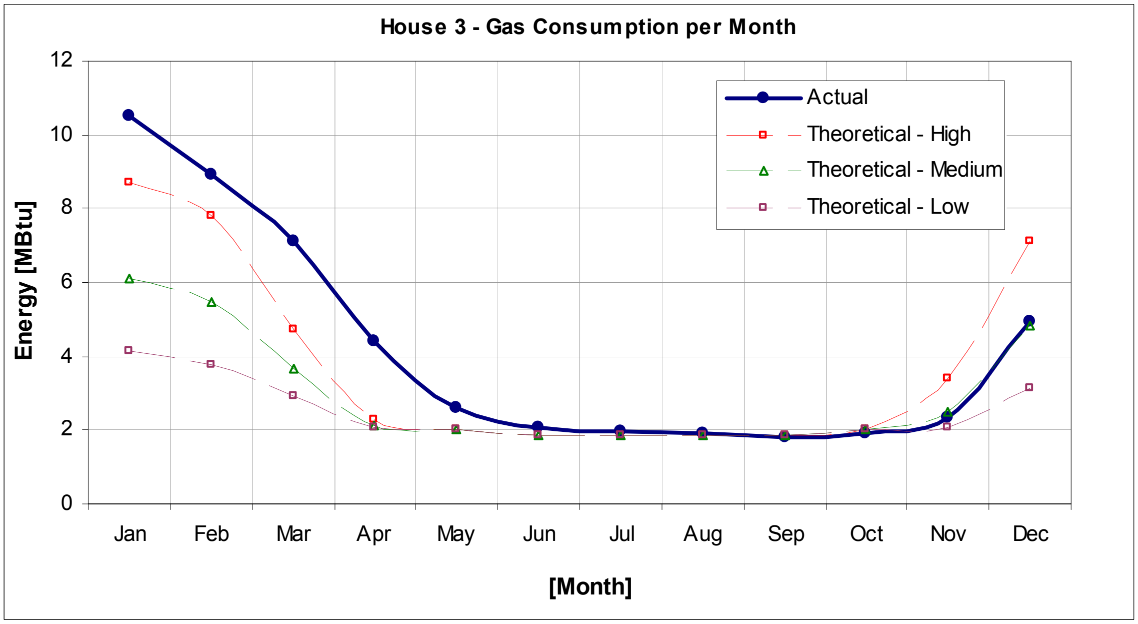

Figure 49: House 3 – Monthly Gas Consumption

The monthly consumption of gas and electricity is combined in the following figure (Figure 50).

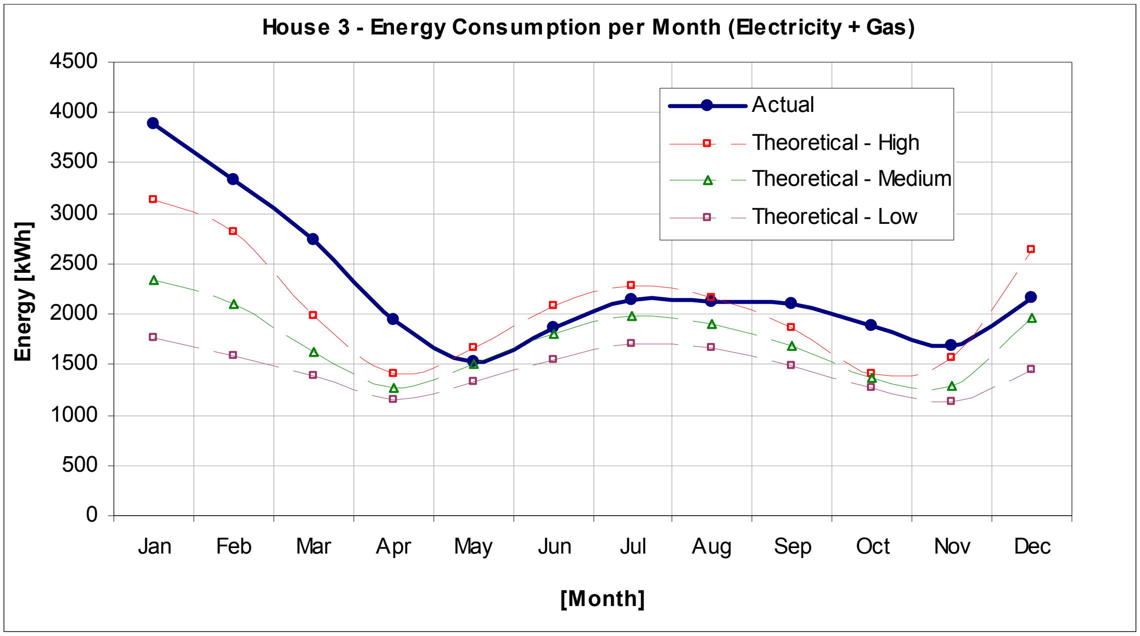

Figure 50: Monthly consumption of electricity and gas for House Type 3

This analysis provided a rough estimate of the energy consumption of houses in New Orleans and is useful for estimating typical monthly and annual energy demand. The CVRMSE value was calculated for comparing the theoretical data to the actual data (the CVRMSE formula is defined in Appendix A.2). The results varied considerably; house categories 3, 4, 5, 6, 7, 8, 9 satisfied the criteria of a CVRMSE<15% while house categories 1, 2 and 10 were outside this range.

Table 11: CVRMSE values for total energy consumption

House Type	High [%]	Medium [%]	Low [%]	Best Fit [%]
1	38.3	54.5	73.7	38.3
2	18.7	35.0	59.2	18.7
3	13.0	26.5	48.8	13.0
4	11.3	21.4	42.0	11.3
5	17.6	12.1	21.1	12.1
6	13.1	22.8	46.4	13.1
7	18.0	10.3	25.5	10.3
8	24.8	13.3	12.7	12.7
9	28.1	17.5	11.5	11.5
10	25.2	34.7	58.7	25.2

The values which are show the best fit are highlighted in Table 11 (yellow is used to highlight CVRMSE values that are less than 15%, and orange is used to highlight CVRMSE values>15%). The fact that some theoretical and actual values fall in to the category of a house with the lowest level of energy consumption house is surprising. One possible explanation is that the level of maintenance of larger homes is greater than smaller homes. This could be due to an investment in maintenance that is proportional to the house's value.

In the SD model the monthly consumption of a house was assumed to be 3555 kWh/month (or an annual energy consumption of 42 660kWh).
Variable name: *Energy_per_House* [kWh/month]

4.6.3 'Post-Use' Phase

The energy used for deconstruction and demolition was based on a review of published data and was not specific to New Orleans.

4.6.3.1 Deconstruction

The EPA defines deconstruction as "the systematic dismantling of a structure […] in order to salvage usable materials" (EPA 2008a). The only value found in existing literature of the energy required to deconstruct houses was 2601 MJ/m^2 (Gao 2001). This is based on a study of deconstruction cited by Gao which was undertaken in Japan; no other studies for the US were found. This appears to be an extremely high value as it is higher than the energy required to construct the structure, hence it was assumed not to be measuring a comparable type of deconstruction. The value used in this model was estimated to be 10 GJ/house which is half of the energy required for construction and transportation, and greater than the value used for demolition.
Variable name: *Deconstruction_Energy* [GJ/house]

4.6.3.2 Demolition

The EPA defines demolition materials "as the debris generated during the construction, renovation, and demolition of buildings" (EPA 2008b). One study suggests that the energy required for demolition is 0.27% of the total energy of the material when transportation, construction and direct embodied energy are considered (Chen 2001). Based on a report from the Consortium for Research on Renewable Industrial Materials (CORRIM) the energy required to demolish several different types of homes is shown in Table 12 (CORRIM 2005).

Table 12: Energy required for demolition (CORRIM, 2005)

House Type	Demolition Energy
	[MJ/m^2]
Wood Stud	3.32
Steel Stud	3.39
Concrete	4.18

SIP and AAC demolition energy values are assumed to be the same as the energy required to demolish the Wood Stud structures. The value used in this model was 7 GJ/house.

Variable name: *Demolition_Energy* [GJ/house].

4.7 Labor Data

For each aspect of housing (house-stage and house construction type), the amount of labor was estimated. This was done using a combination of RS Means and data specific to organizations working in New Orleans. This was used as a metric to track how many labor hours would be required. This labor was assumed to be all of an equal skill level, with a pay rate of 12 $/hr. This value was based on data for New Orleans construction workers (Louisiana Department of Labor 2007).

4.7.1 'Pre-Use' Phase

Labor was estimated using RS Means and the cost of this labor was calculated based on typical rates for construction workers in New Orleans (Table 13). This was calculated by summing the total amount of person-hours required to construct all of the materials identified in Section 4.5.1 using RS Means data for New Orleans (RS Means 2008).

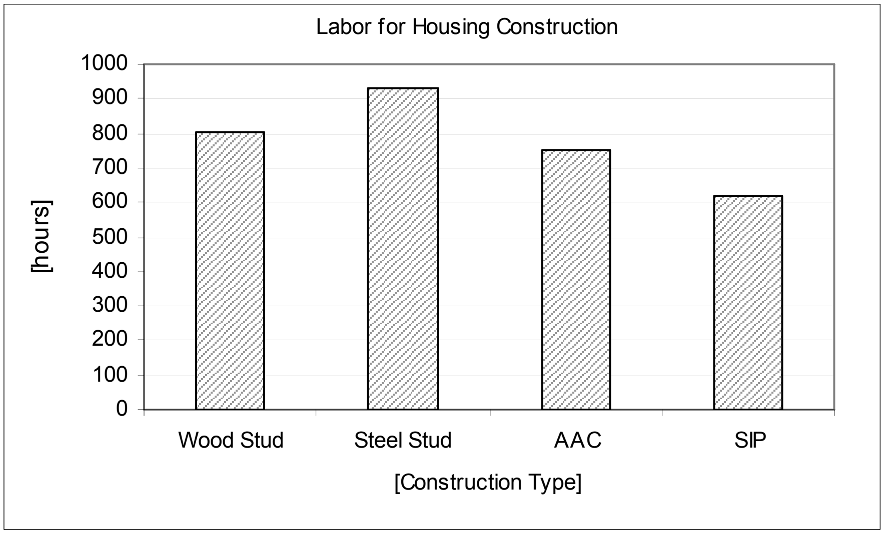

Figure 51: Labor required for construction (considering average house size of 2000 sq ft)

Table 13: Labor required for various assemblies (construction)

Wood Stud	**Steel Stud**	**AAC**	**SIP**
[hr/sq ft]	[hr/sq ft]	[hr/sq ft]	[hr/sq ft]
0.4027	0.4667	0.3771	0.3097

Variable name: *Labor_Hours_Construction*

Figure 52: Labor required for reconstruction (considering average house size of 2000 sq ft)

Table 14: Labor required for various assemblies (refurbishment)

Wood Stud	**Steel Stud**	**AAC**	**SIP**
[hr/sq ft]	[hr/sq ft]	[hr/sq ft]	[hr/sq ft]
0.1668	0.1111	0.0991	0.3090

Variable name: *Labor_Hours_Refurbishment*

4.7.2 'Use Phase'

No labor was assumed to be required during the 'Use' phase of housing as maintenance was considered to be negligible.

4.7.3 'Post-Use' Phase

The amount of labor required during the 'Post-Use' phase is dependant on whether deconstruction or demolition is used at the end of the houses lifetime. The values used in this model are based on theoretical data and data from organizations involved in deconstruction in New Orleans. There is a tipping fee of $400 per dumpster which is estimated to contain 30 cubic yards of material[15 16].

4.7.3.1 Deconstruction

Data was gathered from two organizations who are working on deconstruction in New Orleans, The Green Project[17], and Mercy Corps[18]. Both of these organizations have deconstructed several houses and measured the amount of time required and associated costs. These data are presented in Table 15 and Table 16, and compared to RS Means data.

Table 15: Labor required for Deconstruction

RS Means	New Orleans Data
[hr/sq ft]	[hr/sq ft]
0.320	0.160

Variable name: *POSTUSE_Labor_ Deconstruction*

Table 16: Cost of Deconstruction

RS Means	New Orleans Data
[$/sq ft]	[$/sq ft]
15.0	8.0-13.0

Variable name: *POSTUSE_Cost_Deconstruction*

15 http://www.deconstructioninstitute.com/
16 http://www.louisianarebuilds.info/
17 http://www.thegreenproject.org/
18 http://www.mercycorps.org/topics/hurricanekatrina/1319

4.7.3.2 Demolition

The labor and cost of demolition is described in Table 17 and Table 18.

Table 17: Labor required for Demolition

RS Means	New Orleans Data
[hr/sq ft]	[hr/sq ft]
0.027	0.004

Variable name: *POSTUSE_Labor_Demolition*

Table 18: Cost of Demolition

RS Means	New Orleans Data
[$/sq ft]	[$/sq ft]
2.3	5.0

Variable name: *POSTUSE_Cost_ Demolition*

5 System Dynamics Model – Meso Scale Analysis of New Orleans

This chapter examines the resources required to reconstruct housing and looks at several alternative scenarios due to feedback loops. It is proposed that these feedback loops could be controlled by policy measures, which would strengthen or weaken their effect. The specific behavior of these loops is discussed in Section 5.2 – 5.4. These scenarios are based on the SD diagram (Figure 19) discussed in Chapter 3. A modified version of this model[19] is shown in Figure 53. The data used for these calculations is described in Chapter 4 and the equations are given in Appendix A.3.

5.1 Projected Resource Consumption of New Orleans

Section 5.1 examines the overall system in its current state. The model used to simulate the behavior of the housing stock is shown in Figure 53, with parallel flows of material, energy and labor controlled by this equation. These parallel flows are illustrated in Figure 54, Figure 67 and Figure 69, respectively. The difference between Figure 19 and Figure 53 is the addition of two flows; the inflow to *Housing Stock* is called *New Construction*, and the outflow from *Housing Stock* is called *End of Life Rate*. The flows in Figure 54 are controlled by the variables[20] in Figure 53, with 'convertors' used to change the variables from units of houses to units of kg (or houses/month to kg/month). The models describing flows of energy (Figure 66) and labor (Figure 69) are explained in a similar manner. This simulation also makes the assumption that all of the houses being reconstructed are wood-stud. According to permit data, the majority of houses are being reconstructed (repaired) rather than constructed anew so the assumption in this analysis is that that the original house structure still exists. The majority of houses in New Orleans are of wood-stud (see Figure 91, Appendix B.2).

5.1.1 Material Resources

This section examines the construction materials required to rebuild New Orleans considering the ten materials described in Chapter 4. Figure 54 shows the proposed stock and flow structure with regard to materials.

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[19] The models in this chapter are constructed using Stella. All models in Chapter 3 were drawn using Vensim PLE. Unlike Vensim PLE, Stella does not allow arrow polarities to be shown. Stella was used as this was the program that CDM used to construct the initial model. Where the arrow polarity is unclear, the equations in Appendix A.3 will clarify this.

[20] The variables are referenced using 'ghost variables'; this is comparable to 'shadow variables' in Vensim, mentioned in Section 3.8

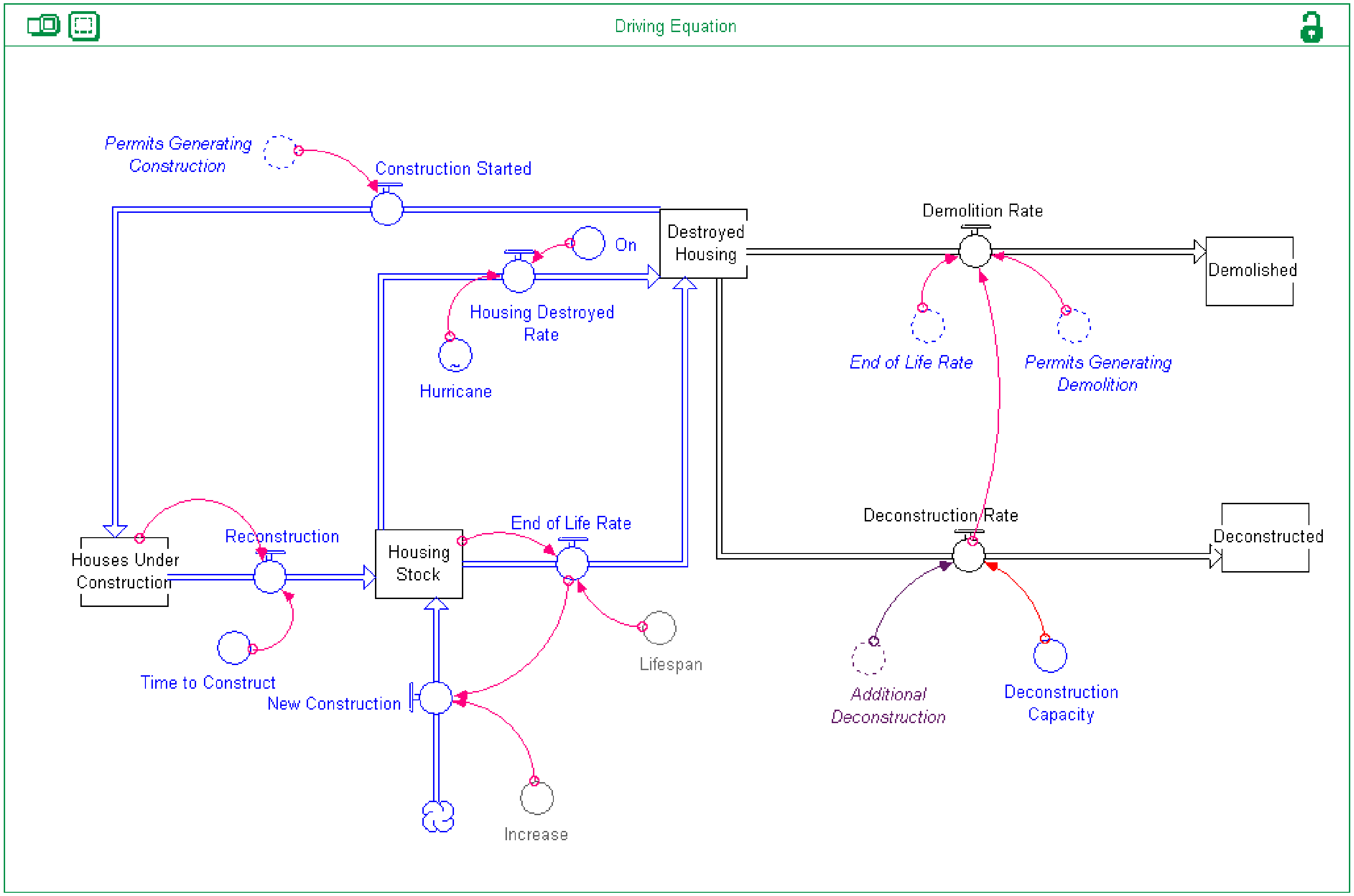

Figure 53: Driving equation for city (similar to Figure 19) with the addition of *New Construction* and *End of Life Rate*

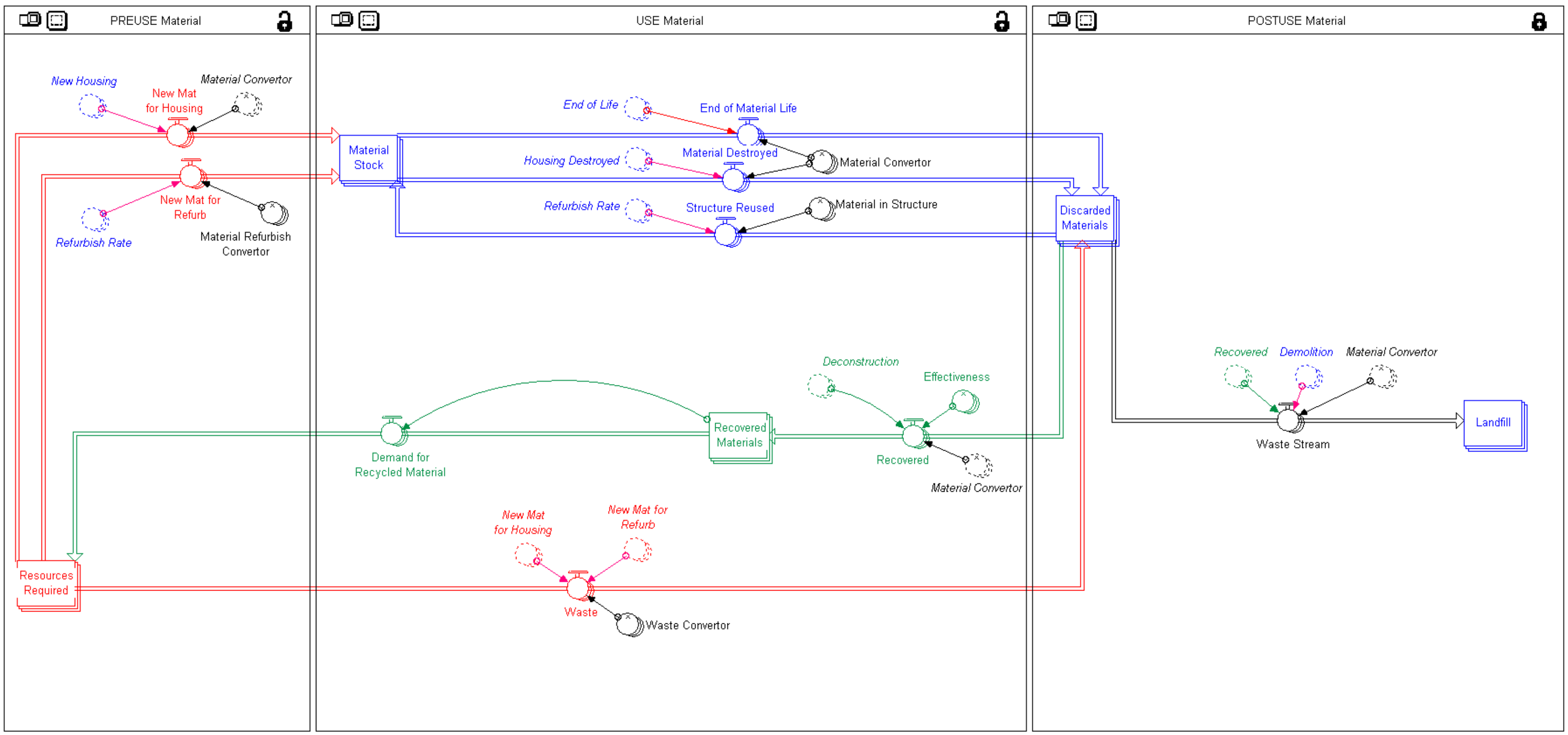

Figure 54: Flows of material driven by the model shown in Figure 53

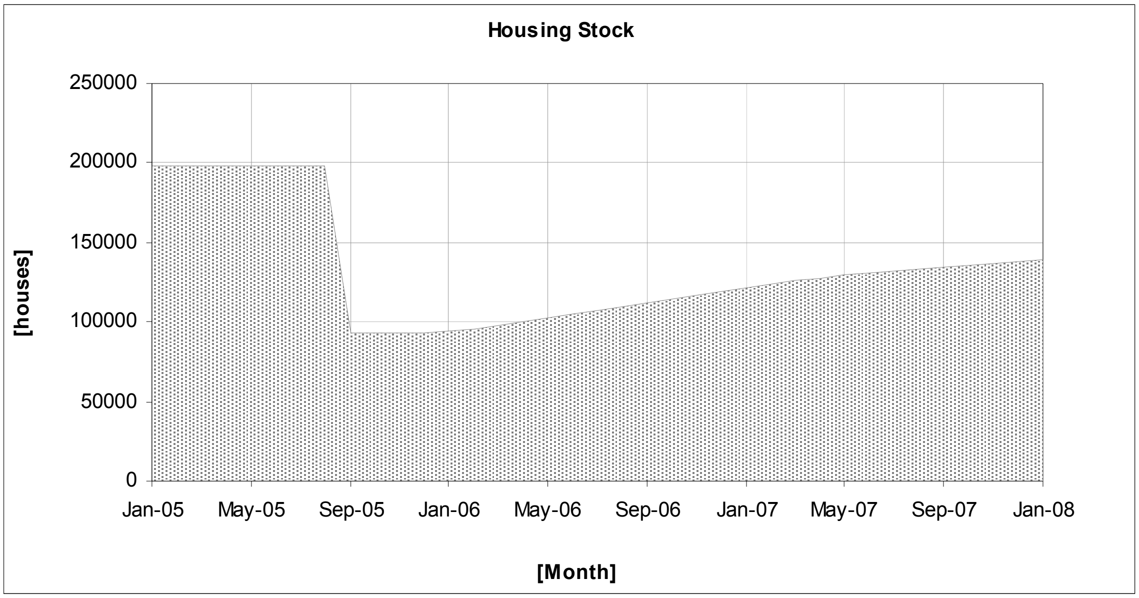

Figure 55: Housing Stock

Figure 55 illustrates the total number of houses in the New Orleans housing stock. All of the values shown in the following graphs should be considered to be estimates as they are based on the assumptions described in Chapter 3 and 4. Figure 56 shows an estimate of the amount of construction material required to rebuild, including both reconstruction and new construction.

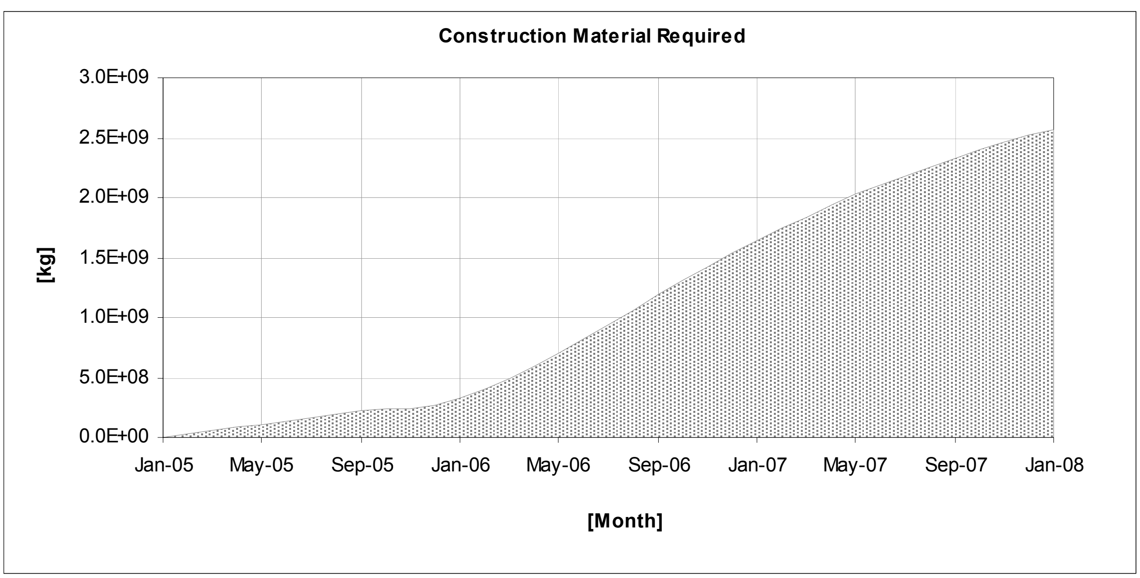

Figure 56: Total construction materials required for Housing Stock

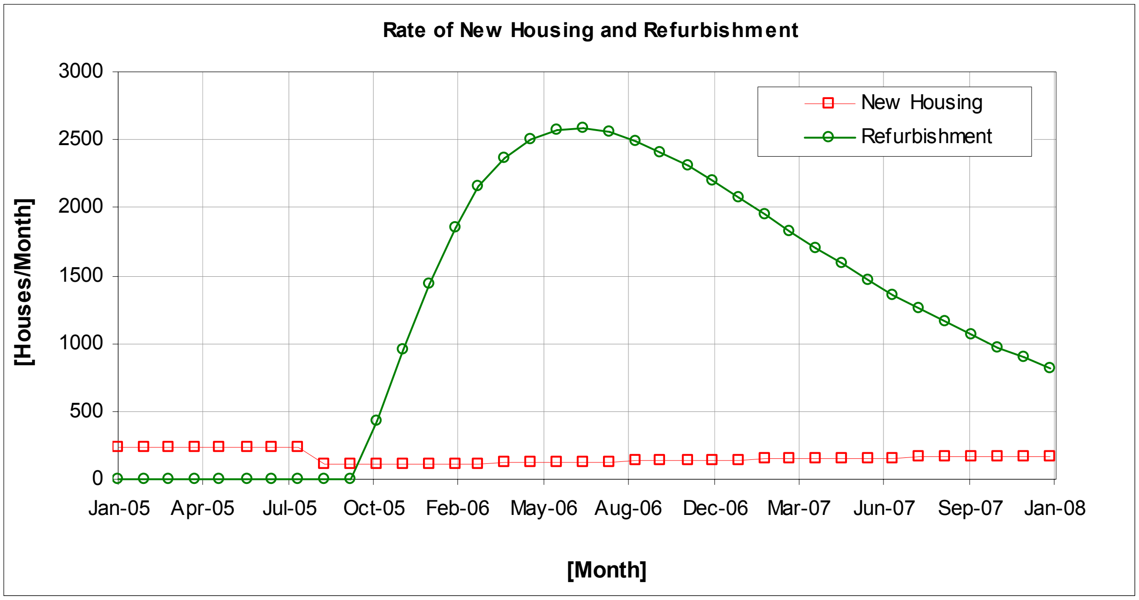

Figure 57: Rate of New Housing and Refurbishment

As illustrated in Figure 57, the majority of houses are being refurbished, when compared to the rate of new house construction. This is based on a particular interpretation of the permit data, and does not consider the case where a house is completely destroyed and rebuilt. Figure 58 illustrates the demand for construction material.

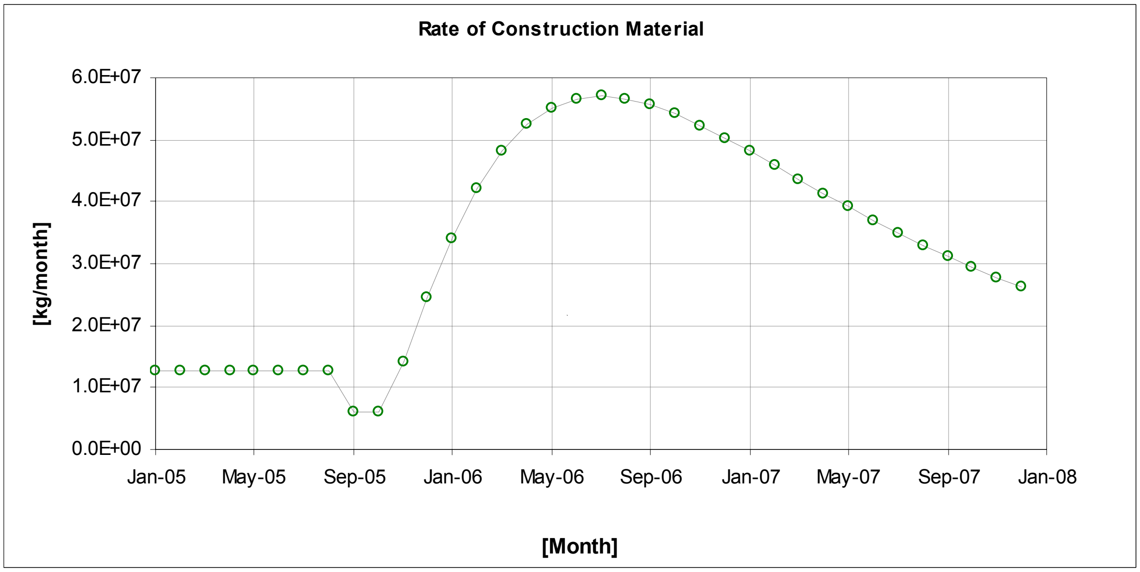

Figure 58: Rate of construction material for reconstruction

The effect of these increasing rates in Figure 57 and Figure 62 can be seen with the rising cost of labor and the Construction Cost Index[21] (ENR 2008), illustrated in Figure 59 and Figure 61.

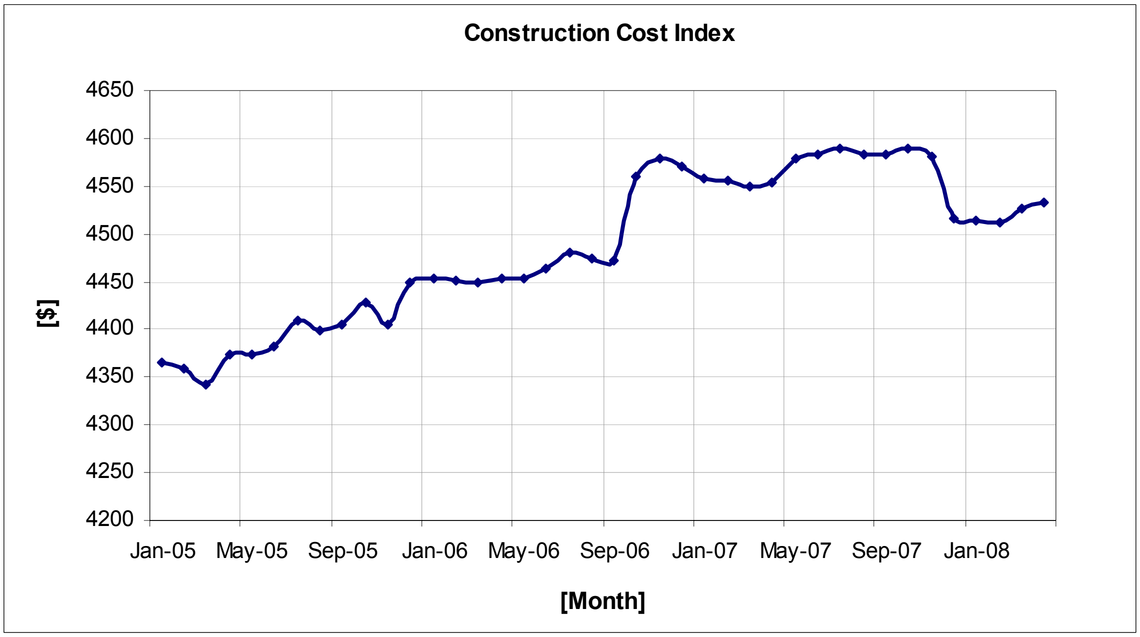

Figure 59: Construction Cost Index for New Orleans (ENR 2008)

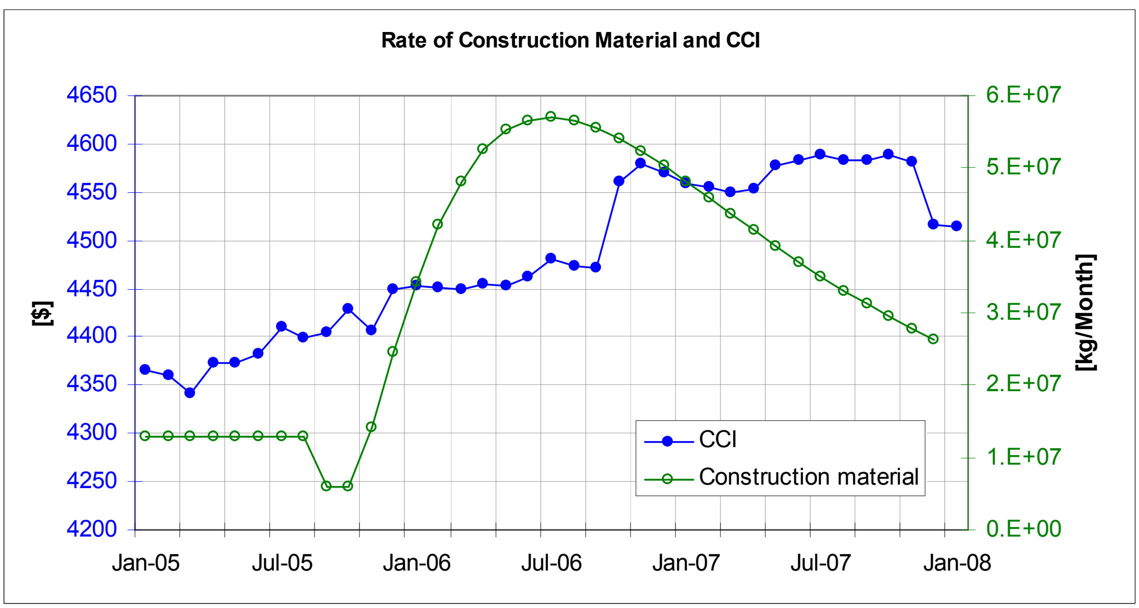

Figure 60: Rate of construction material and CCI values

[21] The Construction Cost Index (CCI) is calculated based on 200 hours of common labor at the 20-city average of common labor rates, plus 25 cwt of standard structural steel shapes at the mill price prior to 1996 and the fabricated 20-city price from 1996, plus 1.128 tons of Portland cement at the 20-city price, plus 1,088 board ft of 2 x 4 lumber at the 20-city price. The city indexes use local prices for portland cement and 2 X 4 lumber and the national average price for structural steel.

The CCI rises steeply following the peak demand for construction materials. This illustrates that there is a link between the simulated peak demand and the price of labor/materials in New Orleans. There appears to be a delay in the system, due to the peak CCI value occurring several months after the peak demand for materials.

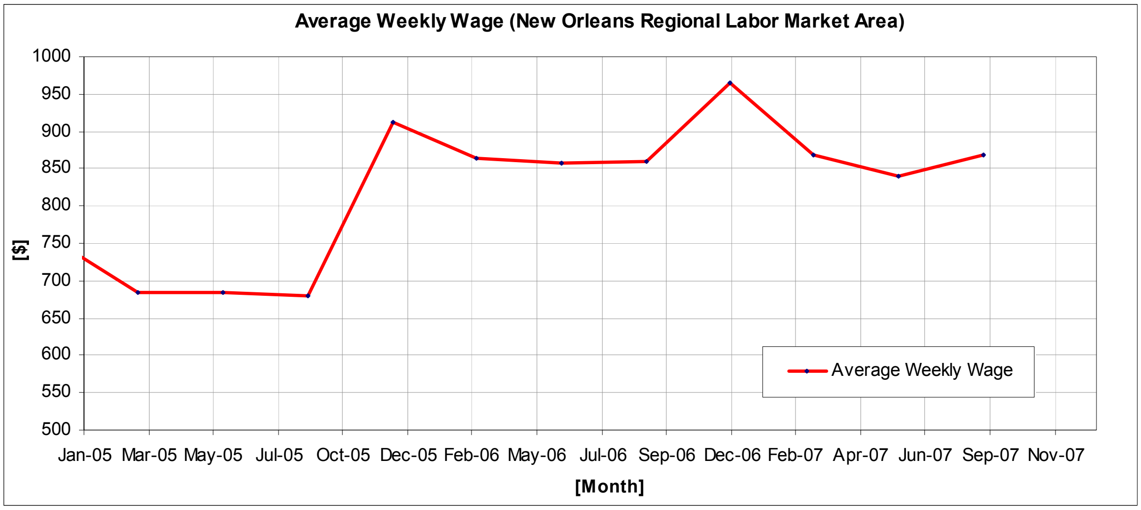

Figure 61: Average weekly wage in New Orleans (BLS 2008)

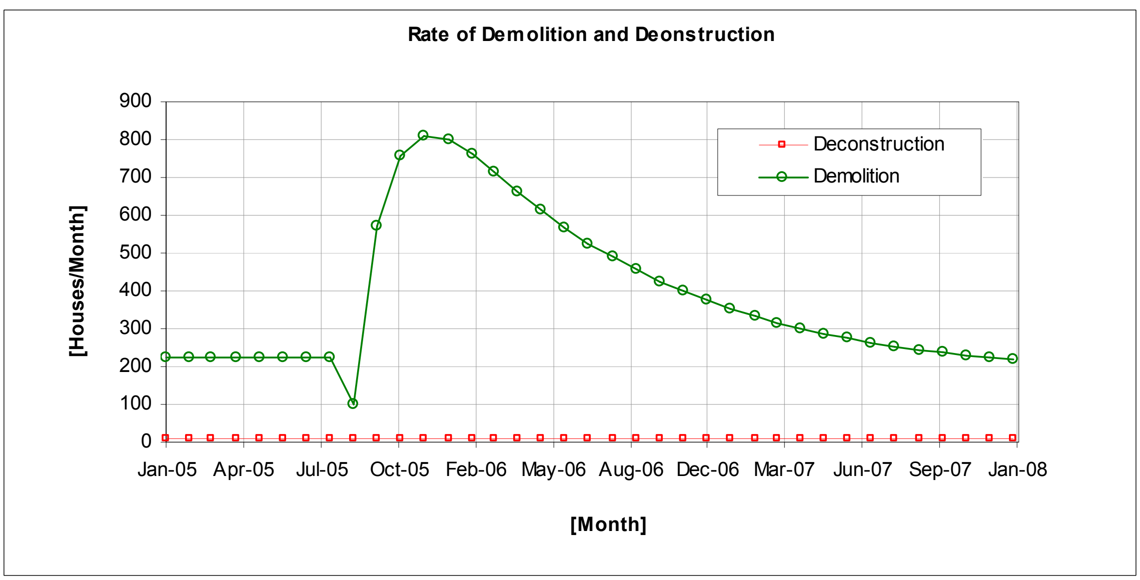

Figure 62: Rate of demolition and deconstruction

Figure 62 and Figure 63 illustrate the rate and stock of deconstructed or demolished houses. From this information, the amount of material that is required to be sent to landfill is shown in Figure 64.

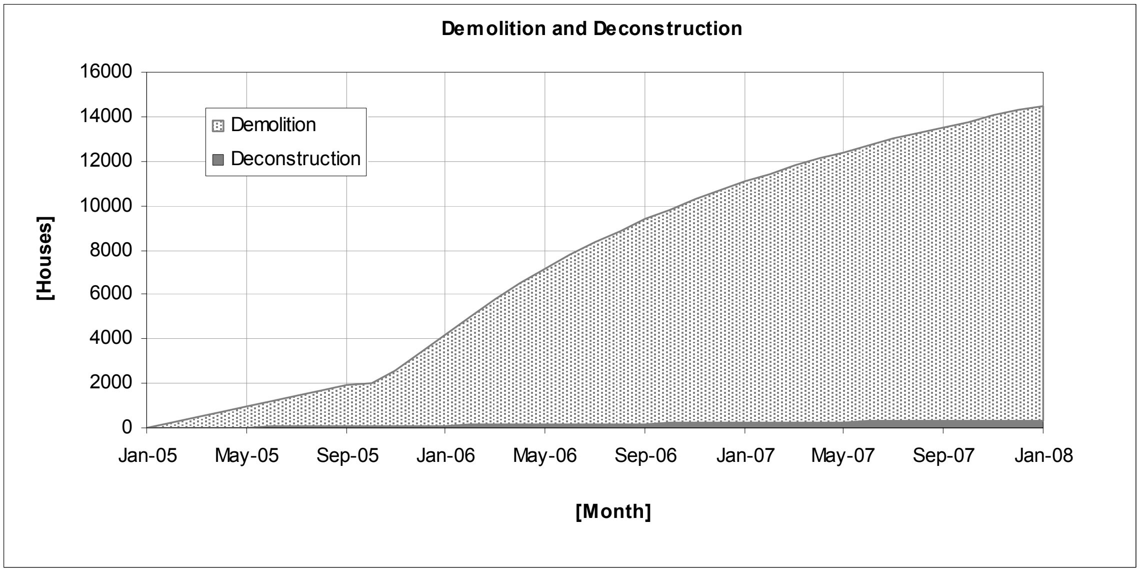

Figure 63: Stock of demolished or deconstructed houses

The rate of deconstruction in this simulation was small (10 houses/month) so the amount of recovered materials is very low.

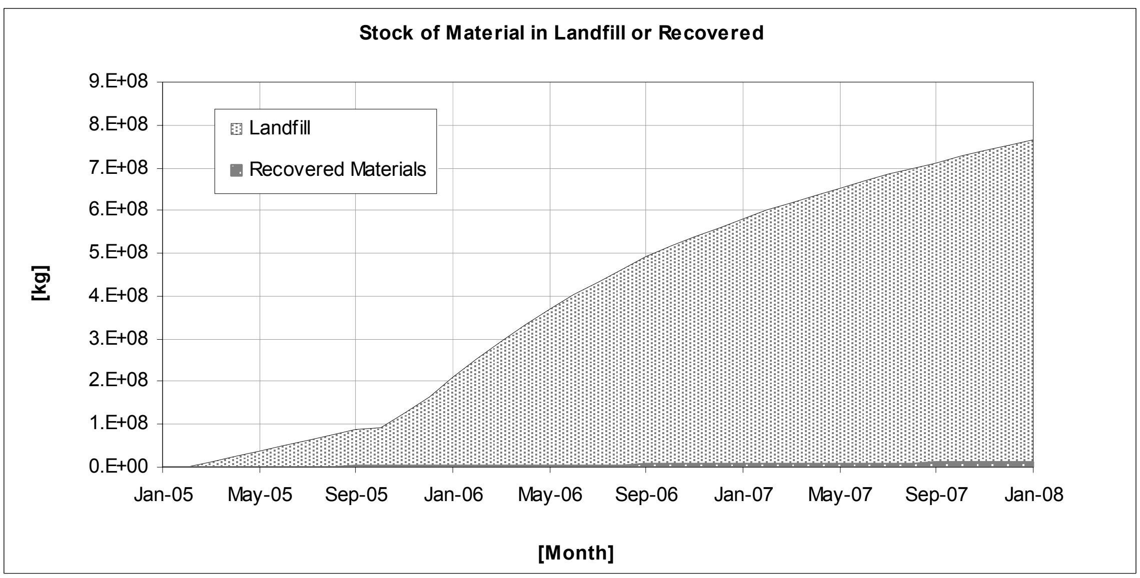

Figure 64: Material sent to landfill or recovered

Viewing this analysis retrospectively clearly highlights when the greatest stresses occur in this system. If this type of model could be provided for policy-makers and government officials, as these events occur, it could assist with planning how to manage resource constraints. In addition, implementing certain policies to reduce the effect of the peak demand could assist in reducing the price of materials.

Energy Resources

The energy that was required for the three phases, 'Pre-Use', 'Use' and 'Post-Use' is illustrated in Figure 65 and Figure 66. The change in slope of Figure 65 (occurring in September 2005) is due to the reduced number of houses needing energy after Hurricane Katrina. Figure 66 illustrates the energy required for the 'Pre-Use' and 'Post-Use' phases. These graphs are derived from the stock and flow diagram in Figure 67, which are similar to Figure 54, and are controlled by the 'driving equation' of the city (Figure 53).

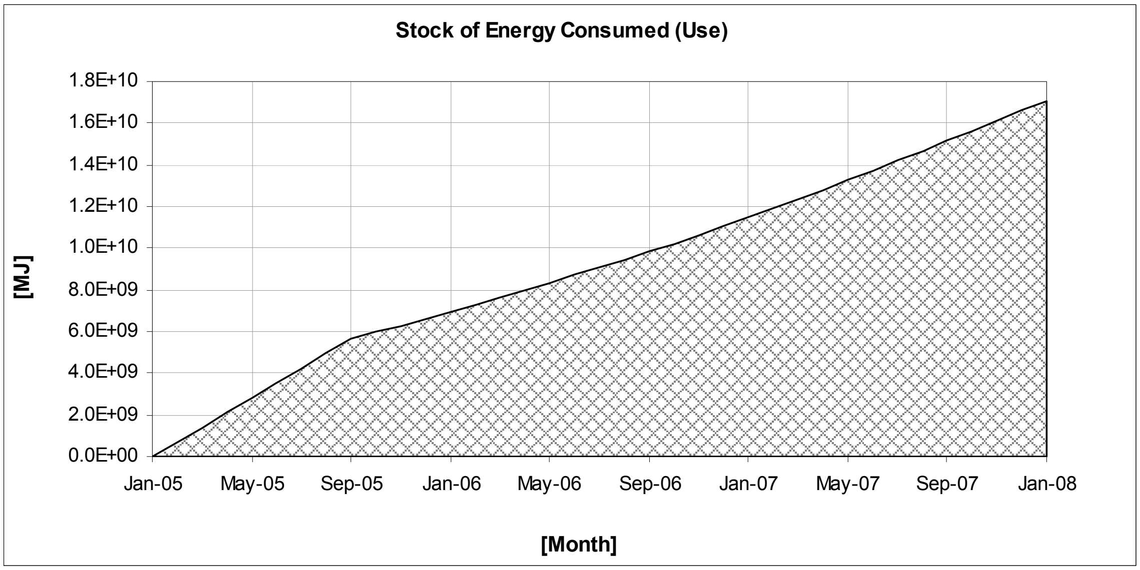

Figure 65: Energy required during the 'Use' phase of the house

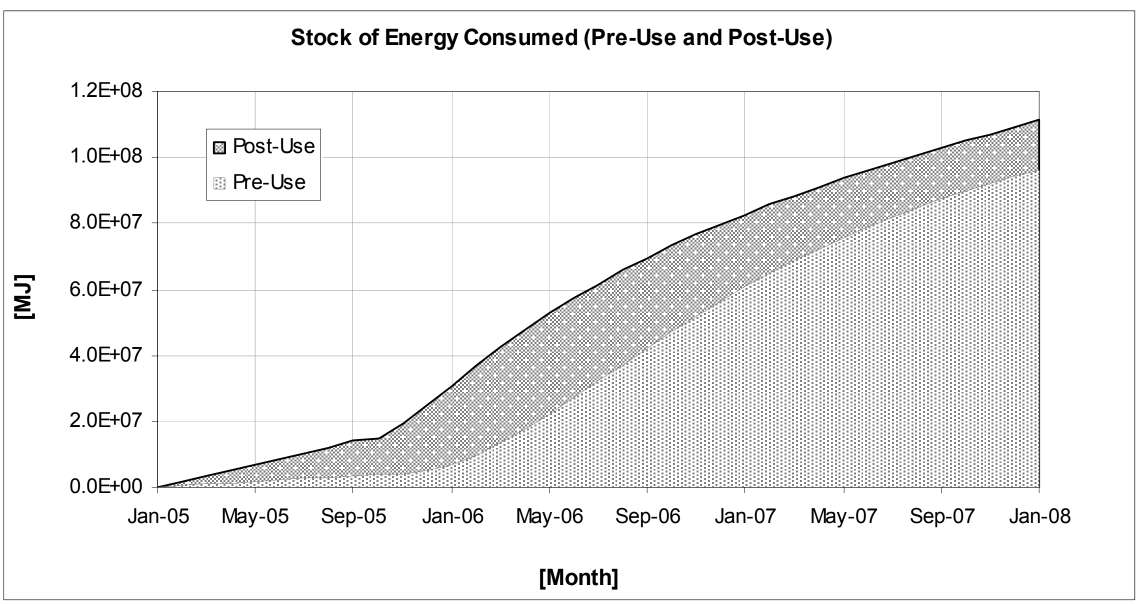

Figure 66: Energy required during the 'Pre-Use' and 'Post-Use' phase

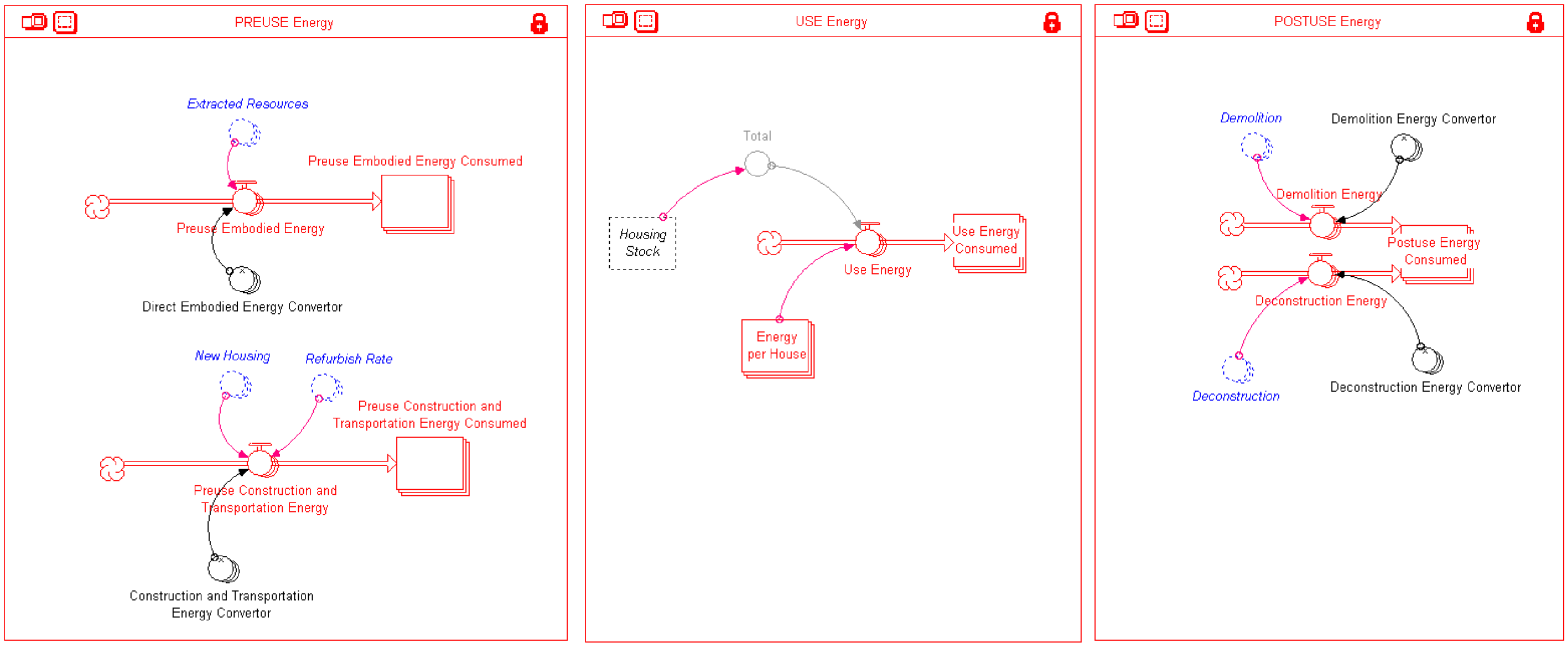

Figure 67: Energy required at various phases of a house's lifetime

'Pre-Use' energy consumption is calculated using the direct embodied energy of the material, as well as the transportation and construction energy. 'Post-Use' is calculated based on the energy required to demolish or deconstruct the house at the end of its lifespan. Sections 4.6.1 and 4.6.3 describe the values used in this study.

5.1.2 Labor Resources

The number of labor hours required for each house was calculated using RS Means in combination with the material required to build a house of 2000 sq ft (RS Means 2008). The number of labor hours required to rebuild the housing stock is shown in Figure 68. There is a significant demand for construction workers (and labor) in the aftermath of the hurricane. In this model, there is not a sufficient level of complexity that the effects of this employment on the city, are simulated. The number of labor hours is dependant entirely on the 'driving equation' and there are no feedback loops identified between labor (Figure 69) and housing (Figure 53) in this model[22].

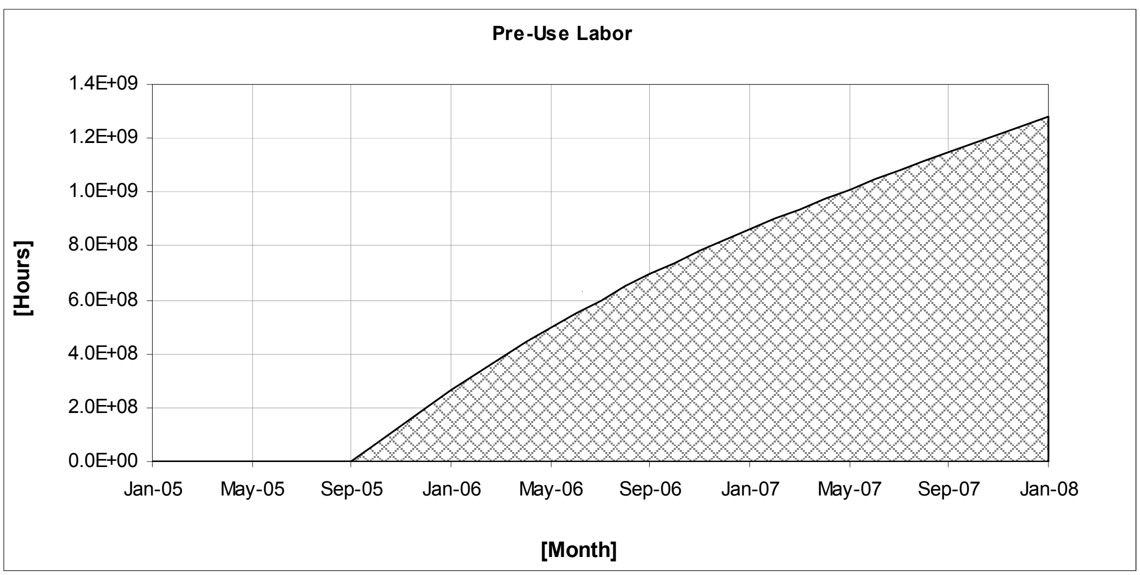

Figure 68: Labor used in reconstruction

[22] In reality, there is a linkage between employment and the demand for housing, but this level of detail is not considered here.

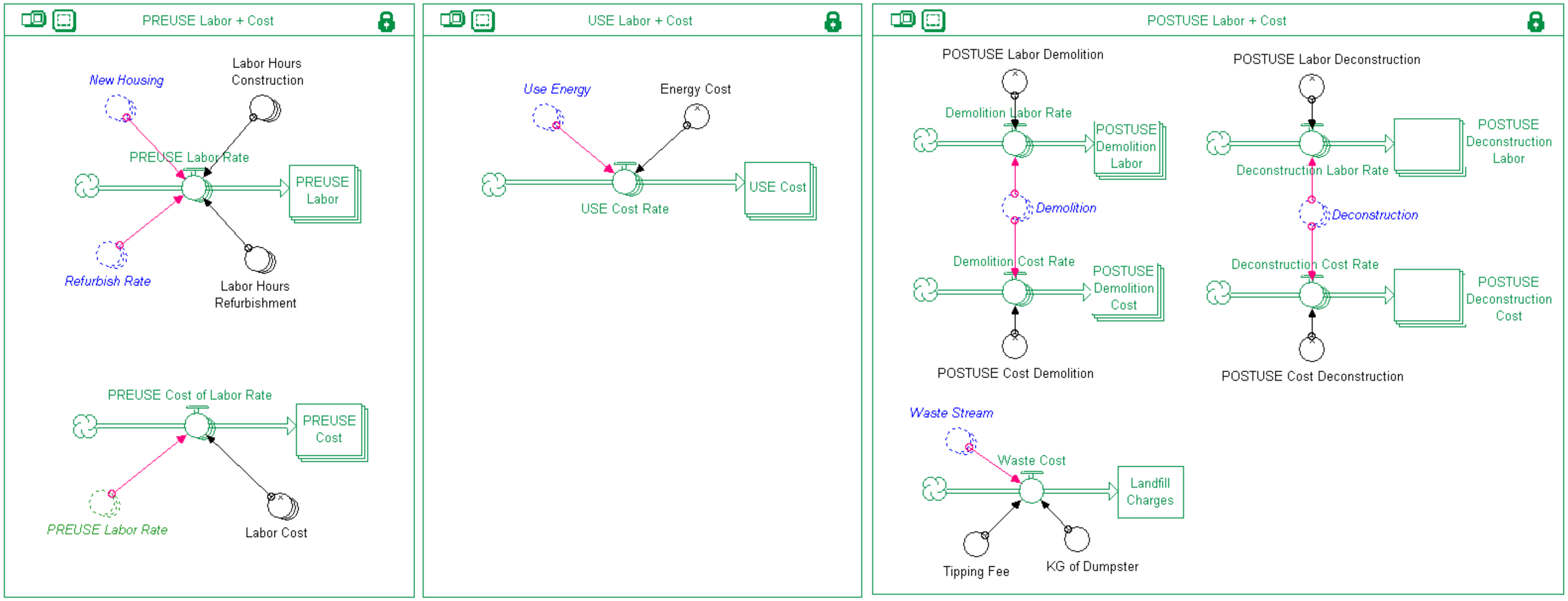

Figure 69: Labor required at various phases of the houses lifetime

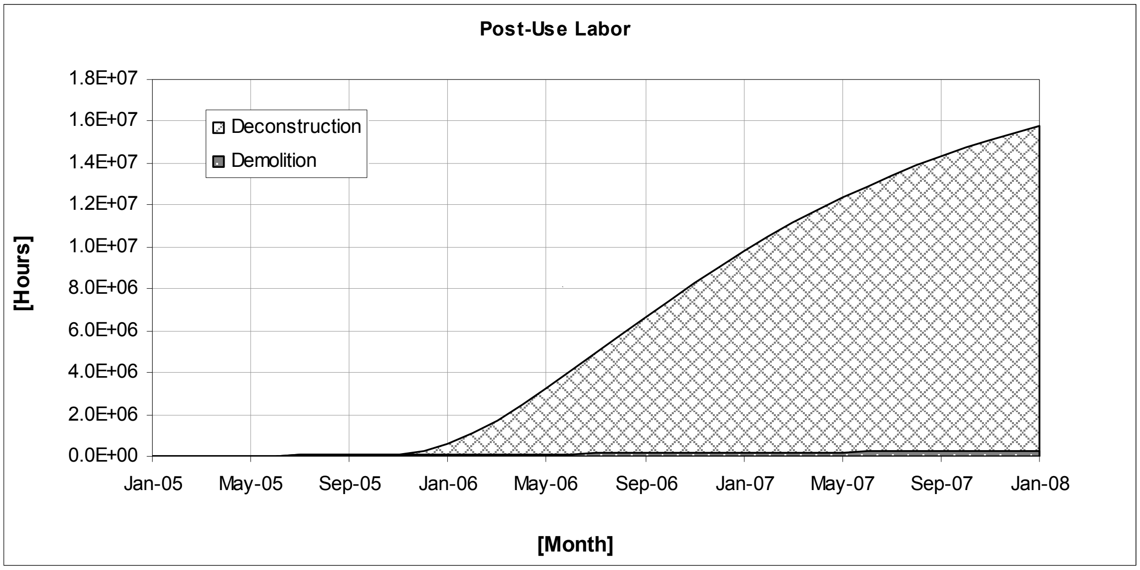

Figure 70: Labor used in demolition or deconstruction

There are clear labor benefits when deconstruction is compared to demolition, as illustrated in Figure 71. As mentioned previously, the majority of houses are demolished so the current labor required for deconstruction is insignificant.

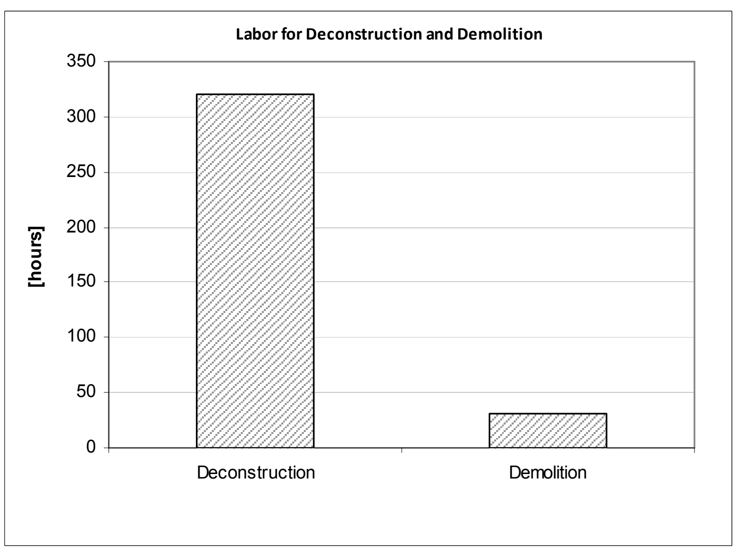

Figure 71: Labor hours required for deconstruction or demolition of a 2000 sq ft house

5.2 Energy Conservation Feedback Loop

A feedback loop which considered the effect of policy incentives to encourage energy conservation was defined. This proposed chain of causality is illustrated in Figure 72. This was incorporated into the stock and flow diagram, with the structure shown in Figure 73 .

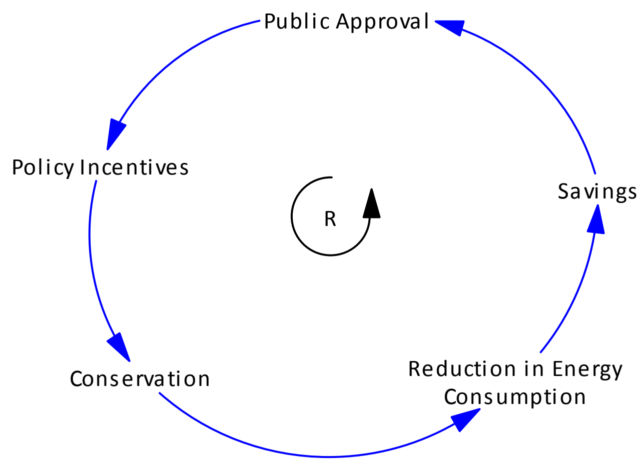

Figure 72: Schematic for Investment in Conservation

Using BEopt, simulations were carried out which compared the energy consumption levels of houses based on different levels of housing performance. The cost estimates were made using RS Means (RS Means 2008). The amount of energy used per month by an average 2000 sq ft house is 3555 kWh[23] and the cost of electricity is $0.098/kWh[24]. The *Length of Policy Time* (Figure 73) is the length of time that an incentive is given to reduce consumption. In this instance, the policy time is 24 months, and $30 per month is invested, while the policy is in place. This loop is completed, based on the premise that if there are sufficient savings from conservation, that there will be sufficient public demand to force the process to continue. The model structure has an outflow from *Energy per House,* which reduces the level of energy used per month, based on the amount of money invested in conservation measures. This policy of $30/month could be in the form of a rebate, or utility bill discount. The motivation for a utility company to invest in this scheme could be to reduce peak-load demand when the cost to produce energy for the utility company is most expensive.

[23] Both gas and electricity are used to calculate this value.
[24] EIA. http://www.eia.doe.gov/cneaf/electricity/page/sales_revenue.xls

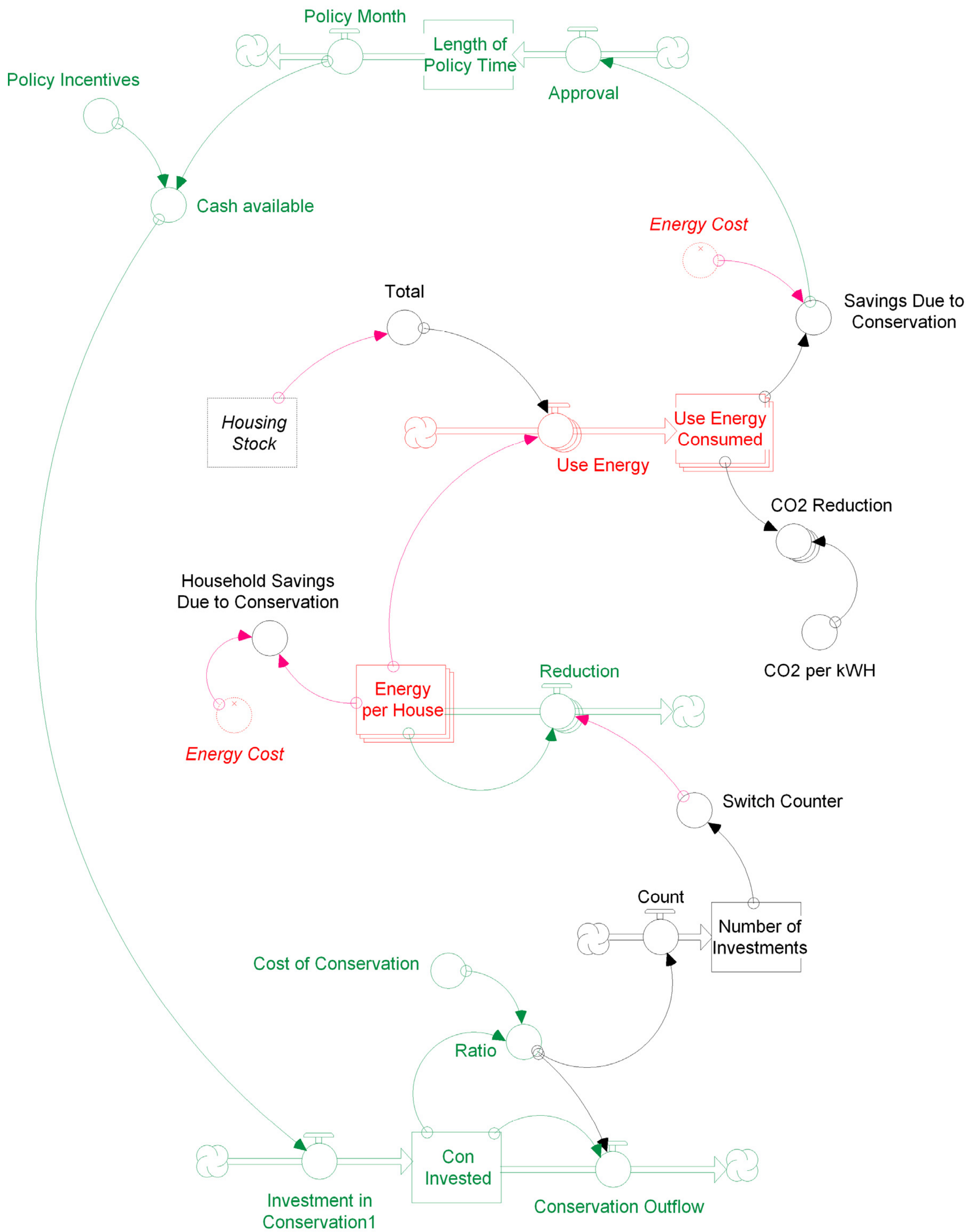

Figure 73: Schematic for Investment in Conservation (loop shown in green)

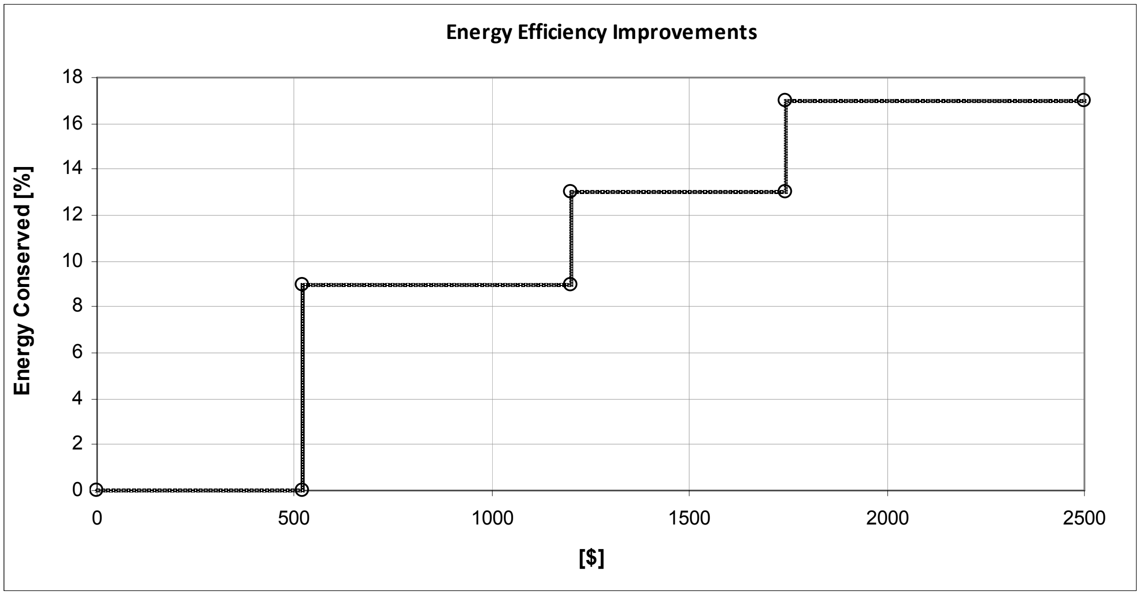

Figure 74: $ investment/Efficiency relationship of total $ invested (not cumulative)

Figure 74 shows the relationship between the amount of money invested in energy conservation, and residential energy efficiency improvements. This performance level is achieved by retrofitting houses with specific options chosen in relation to construction. The level of energy consumption per month is shown in Figure 75 for a house that has invested in conservation, and one that has not. These analyses are based on data from BEopt.

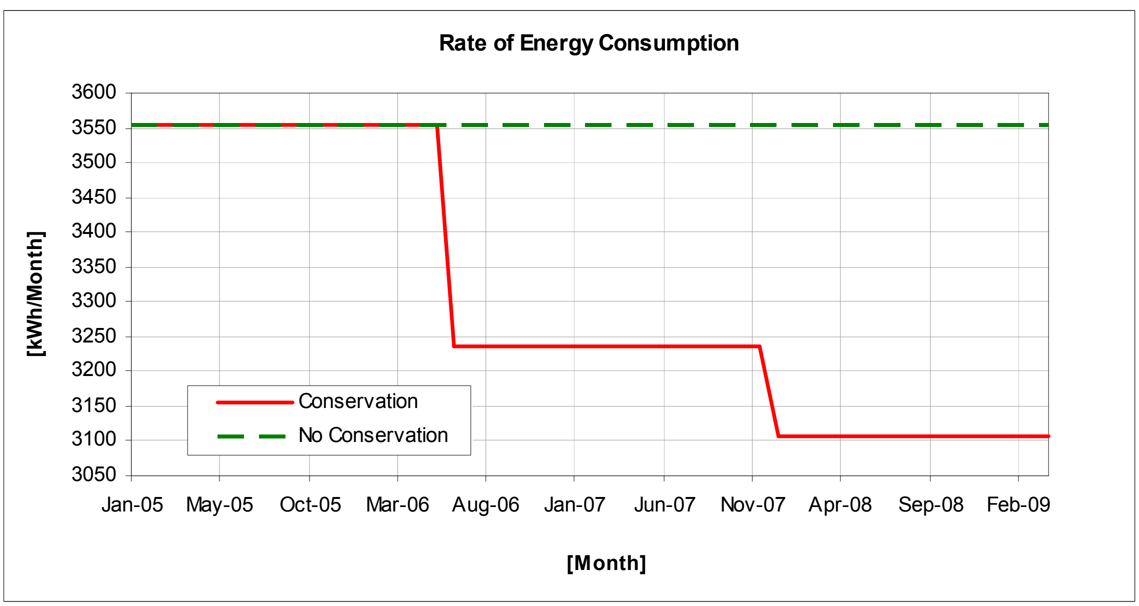

Figure 75: Energy used per month for 2000 sq ft house

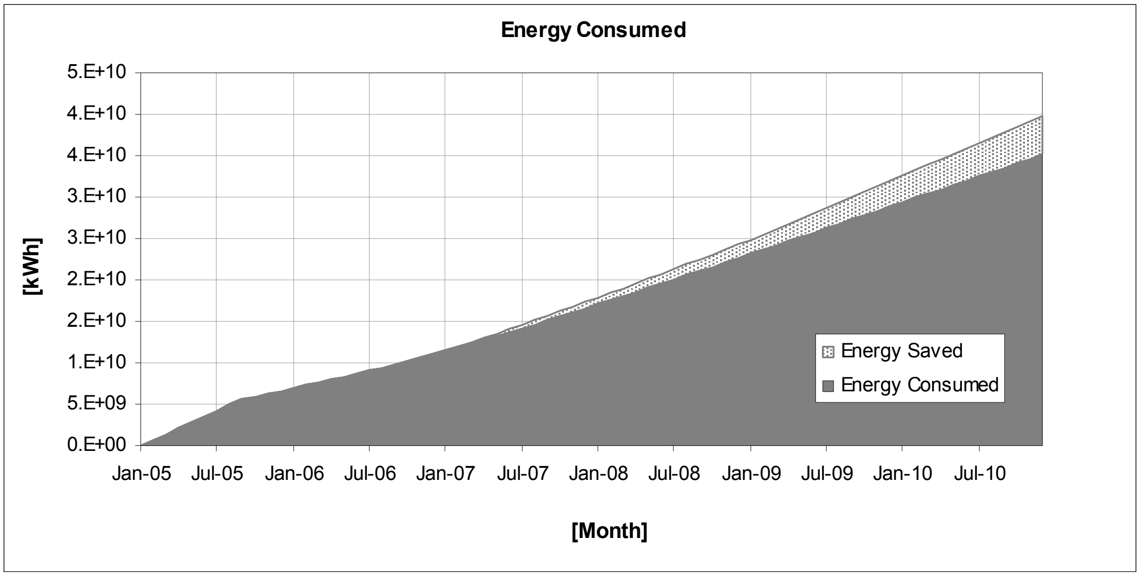

Figure 76: Total energy consumption of electricity for housing stock in New Orleans

Based on the improvements described above, the effect of the proposed conservation scheme is illustrated in Figure 76. The total reduction in energy consumption for New Orleans is shown. These improvements would save a total of 4.69 x 10^9 kWh after 72 months and reduce the total amount of CO_2 emitted by 482 tons.

5.3 Deconstruction Feedback Loop

The feedback loop proposed in Figure 77 illustrates the effects of a policy to aid deconstruction by making it cheaper than demolition. This could be carried out by providing a subsidy for deconstruction, or a tax to increase the cost of demolition. The goal of this policy is to encourage home-owners to choose deconstruction. When this is viewed in the context of the city, there are several benefits quantified which may not be initially obvious.

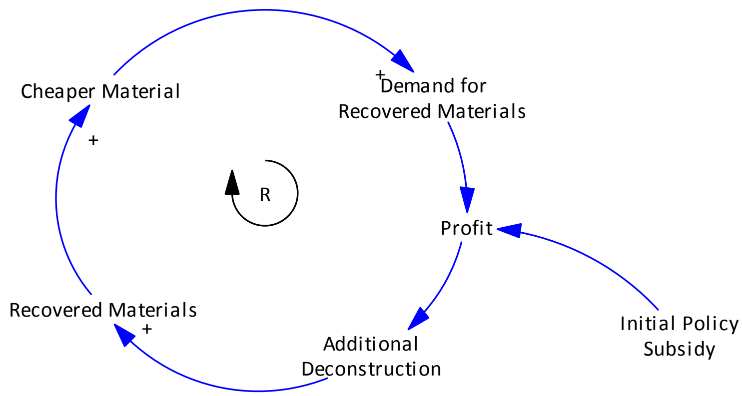

Figure 77: Proposed Deconstruction/Demolition reinforcing loop

This causal loop is illustrated with the stock and flow diagram in Figure 78. Figure 77 illustrates the pattern of behavior that would occur if this reinforcing loop was strengthened with an appropriate policy. The time period for this to occur, or the causal relationships are not calculated in this model, but this general pattern is illustrated as a useful example of the effects of a policy.

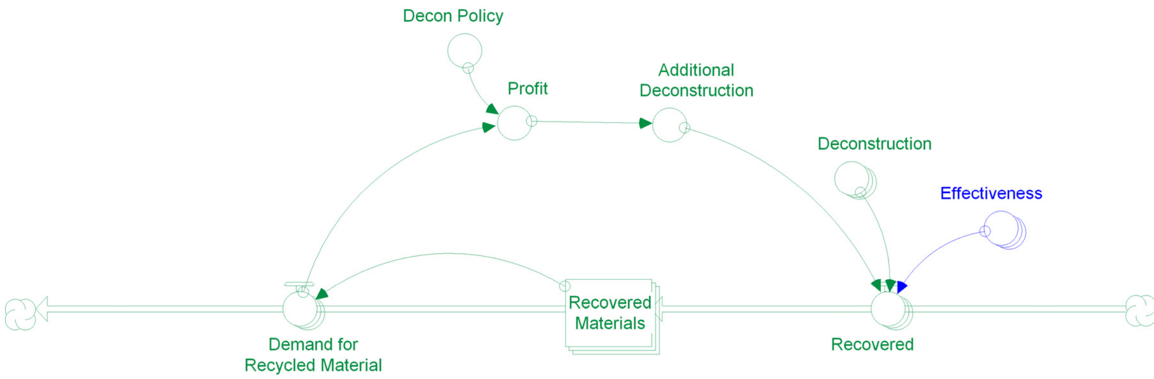

Figure 78: Proposed reinforcing feedback loop for deconstruction (stock and flow diagram)

The principle being illustrated here, is that promoting deconstruction by price is a useful leverage point in the system as it can be used to regulate what happens further downstream. By encouraging an increase in deconstruction over demolition, this would result in decreased flows going to landfill. This illustrates a useful mechanism for reducing the flow of material into a landfill. In addition, it could reduce the price of some construction materials during the times of peak demand.

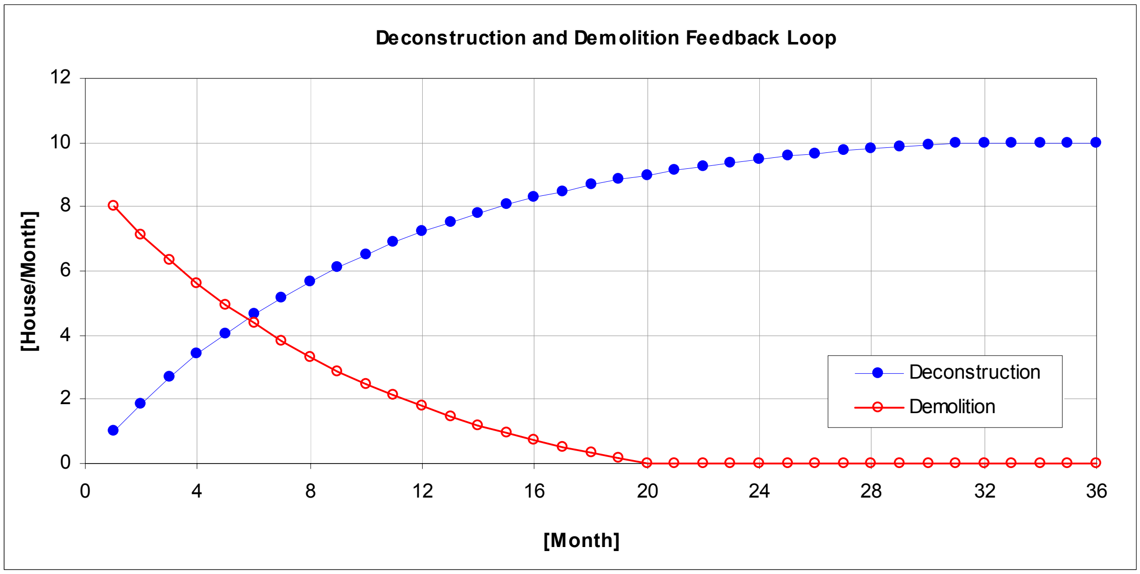

Figure 79: Proposed reinforcing feedback loop for deconstruction

Based on the data gathered, the deconstruction subsidy (or demolition tax) required to cause this change is \$3-4 per sq ft. This assumes that the policy is targeting the houses that are easiest to deconstruct. The cost of demolition is \$5 per square foot (Section 4.7.3.1) with the cost of deconstruction somewhere between \$8-13. The price range for deconstruction is due to variations in the structural integrity of the house which influence the ease of deconstruction.

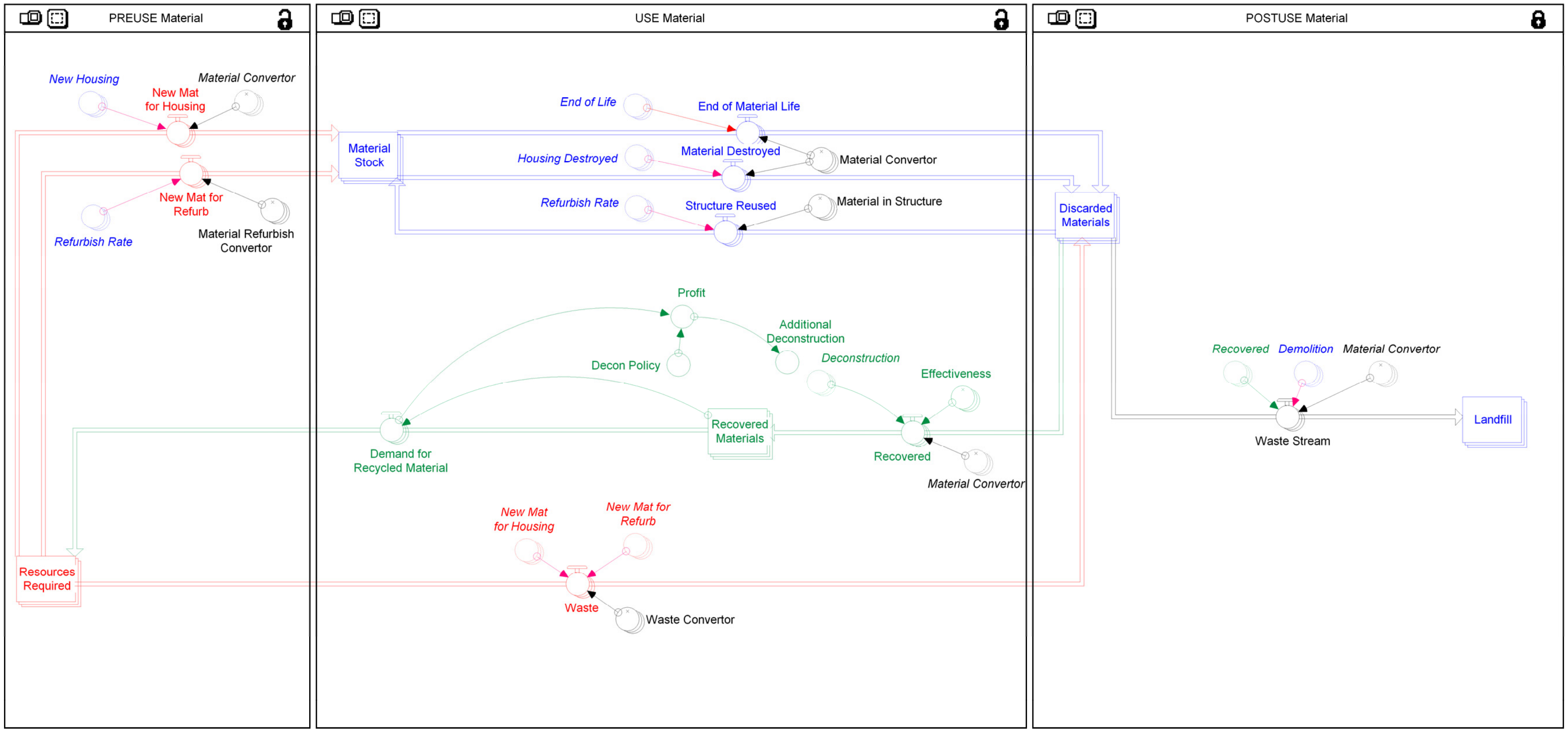

Figure 80: Feedback loop illustrating deconstruction (part of model in green) and demolition options

However, in the specific case of New Orleans, there was an urgent need to remove destroyed houses as quickly as possible and demolition was provided by the city free of charge. This deconstruction policy is a measure that would need to be introduced with caution, as if attempted on a large scale, the additional time delay (and capacity constraint) could further disrupt the rate of recovery in New Orleans.

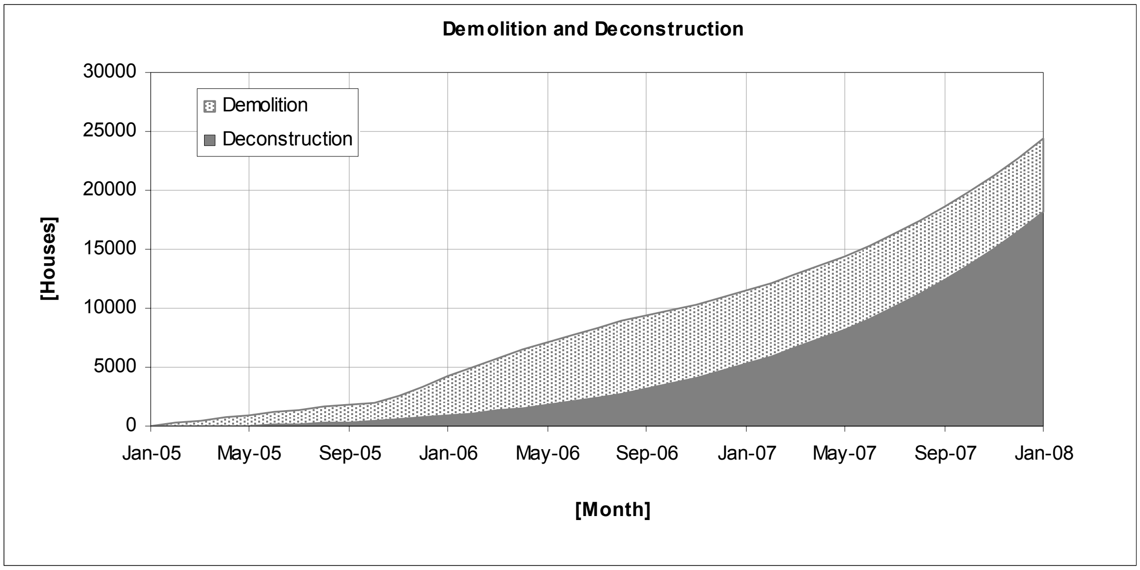

Figure 81: Optimistic scenario – deconstruction becomes the preferred option

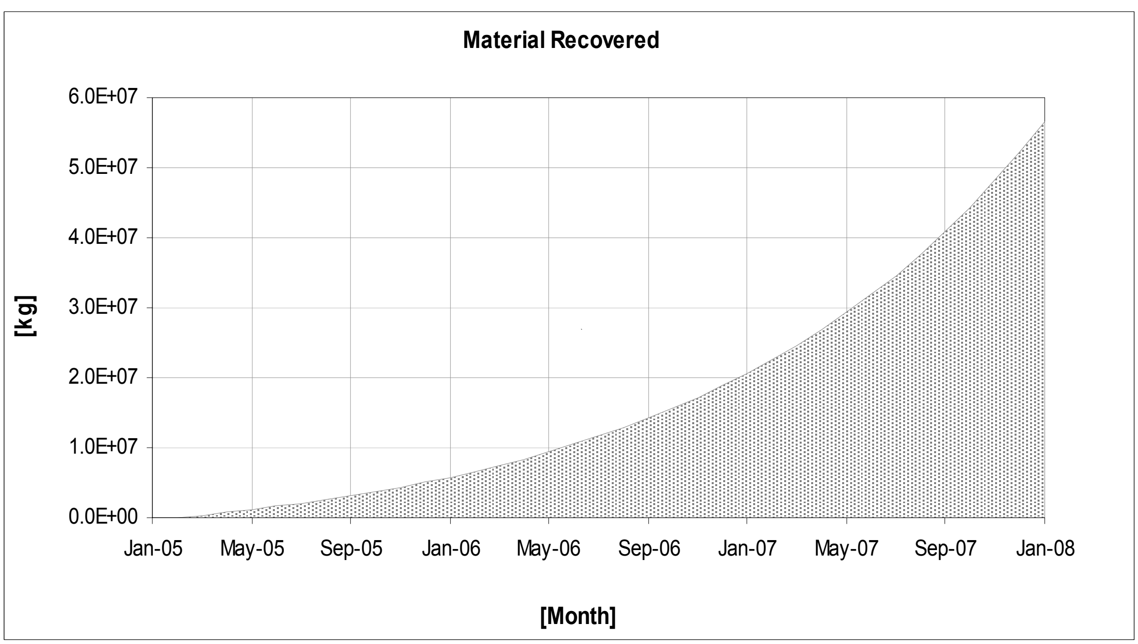

Figure 82: Total material recovered due to deconstruction

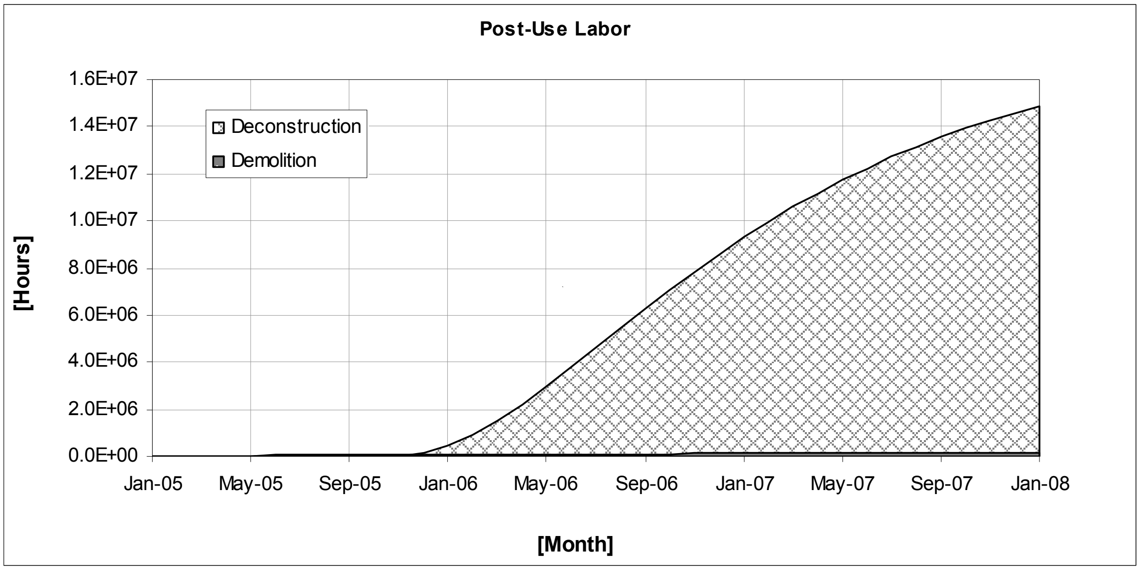

Figure 83: Labor due to deconstruction and demolition

The benefits of deconstruction are significant – there is an increased amount of labor required (Figure 83) and there are energy savings due to the reuse of material which is viewed as having a negligible amount of embodied energy (Figure 84).

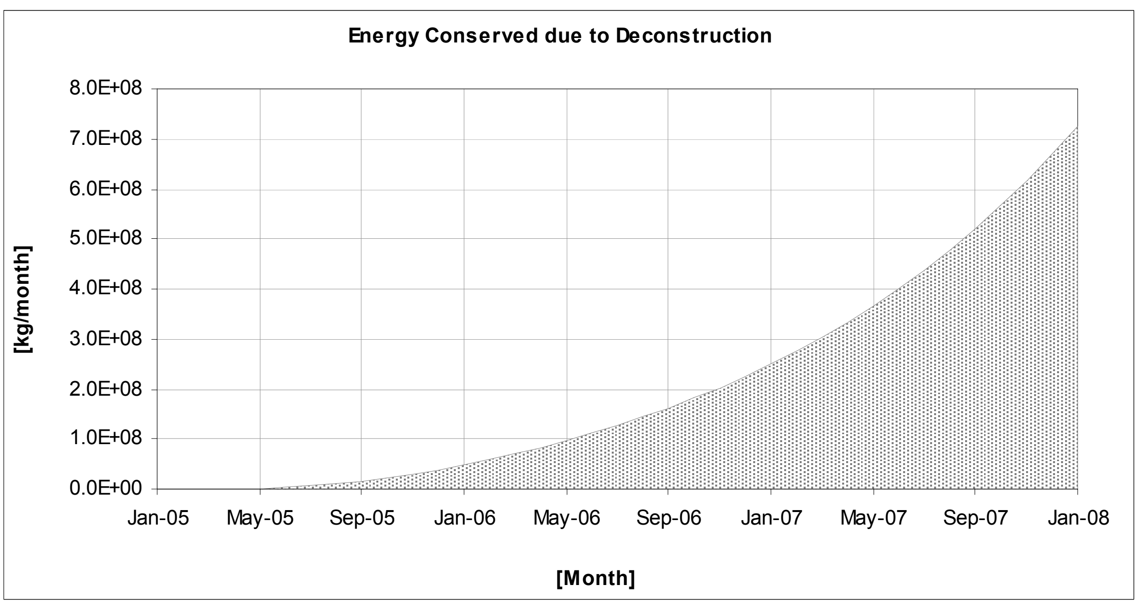

Figure 84: Energy saved due to material reuse as a result of deconstruction

5.4 Landfill and Dumping Feedback Loops

This feedback loop illustrates the dynamics of landfill charges and dumping charges. This example is shown for the purposes of illustrating a particular behavior, and is not based on values from New Orleans. Figure 85 shows a balancing and reinforcing loop which is dependant on the cost of disposing of waste material. In this example, material can be disposed of in a landfill or by dumping.

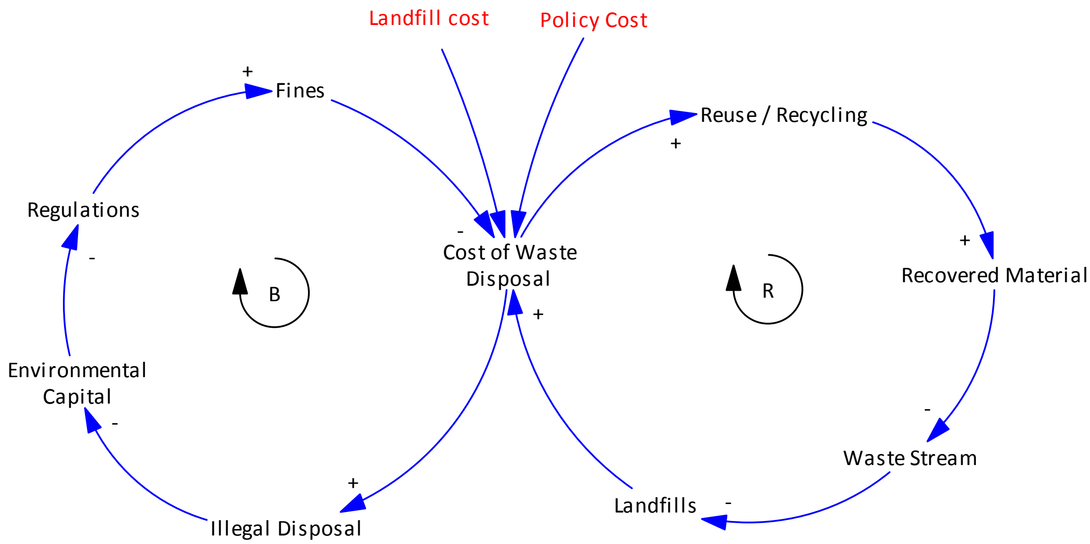

Figure 85: Reinforcing and balancing loops for landfill and dumping

The cost of sending material to a landfill is calculated as being proportional to the amount of space left in the landfill. Similarly the fines due to dumping are proportional to the volume of material that is dumped, as an increase in dumping results in an increase in fines to deter further dumping. The effect of time delays is not considered in these two loops. Figure 86 illustrates the interaction between the dumping and landfill flows, in a stock and flow diagram.

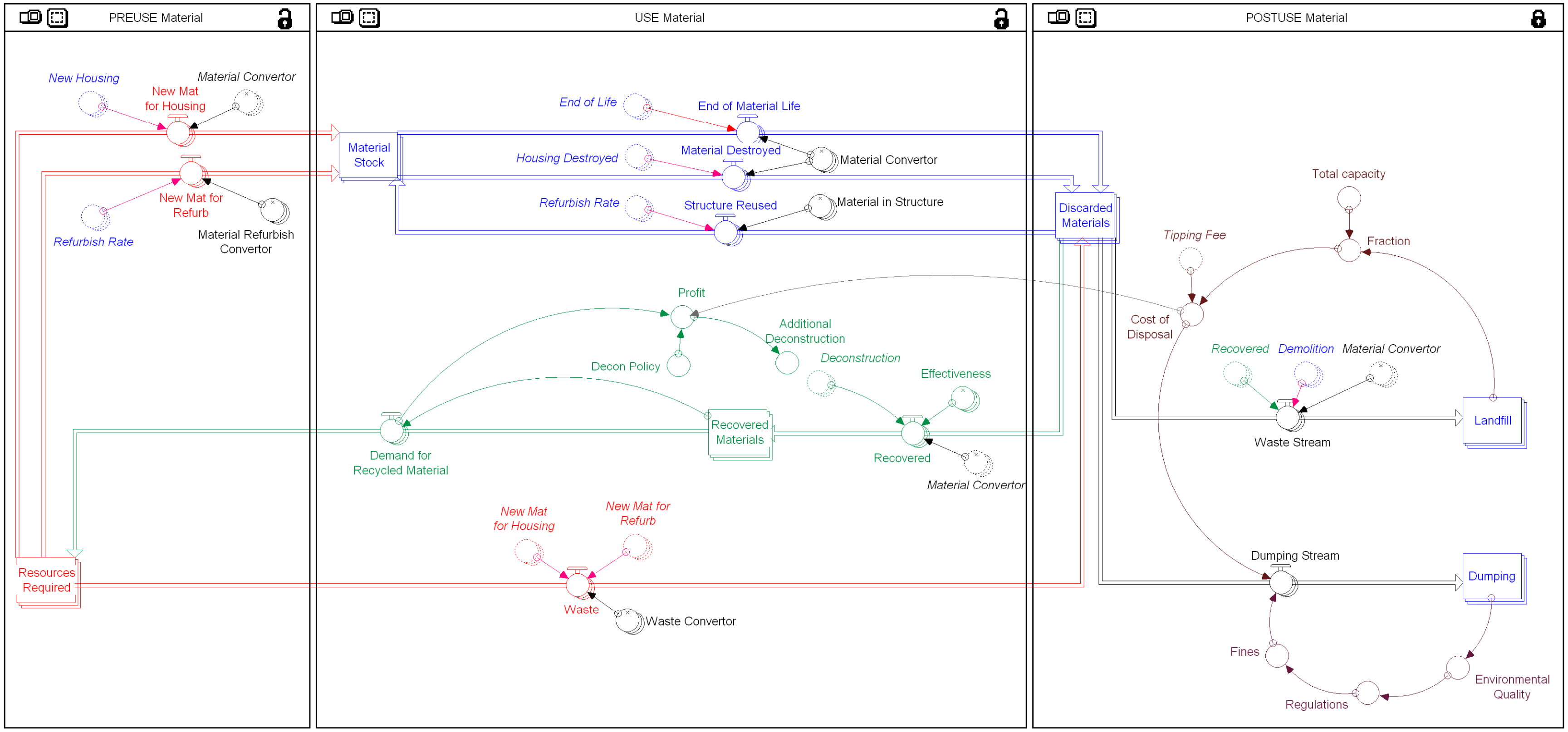

Figure 86: Material flows considering the interaction between landfill and dumping

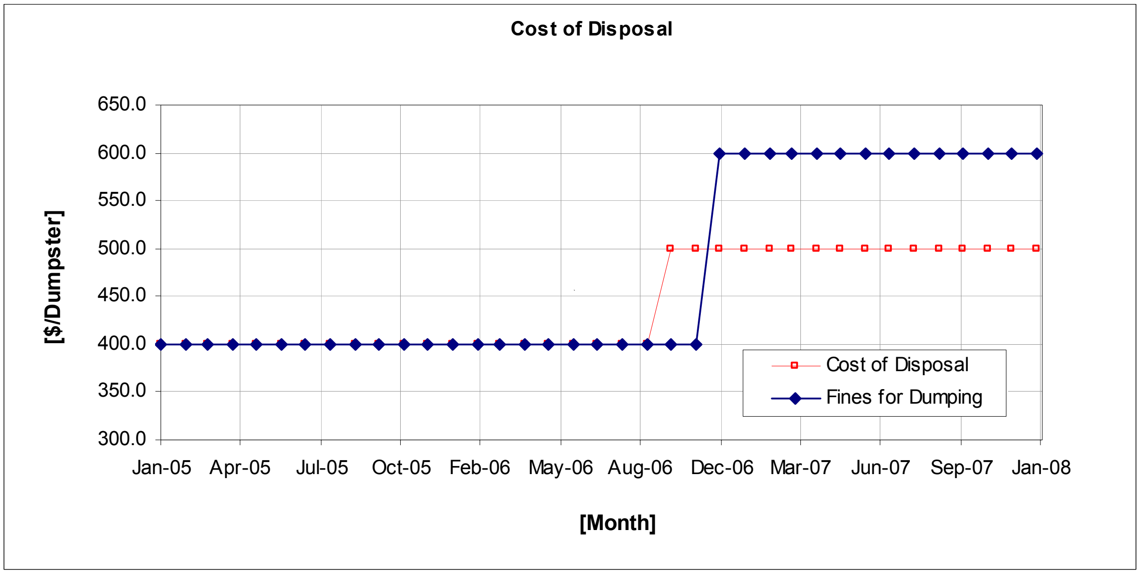

Figure 87: Cost of disposal and dumping per dumpster (30 cubic yards of material)

In this example, values have been chosen that illustrate the dynamics of a particular scenario; where the cost of sending material to a landfill becomes more expensive than paying fines due to dumping. Hence there is a surge in the amount of materials being dumped (Figure 88), which results in environmental degradation (stock of dumped material shown in Figure 89). This motivates policy makers to increase the penalties for dumping so that the fine is increased to the level where it is more expensive than sending material to landfill. This approach prevents further dumping.

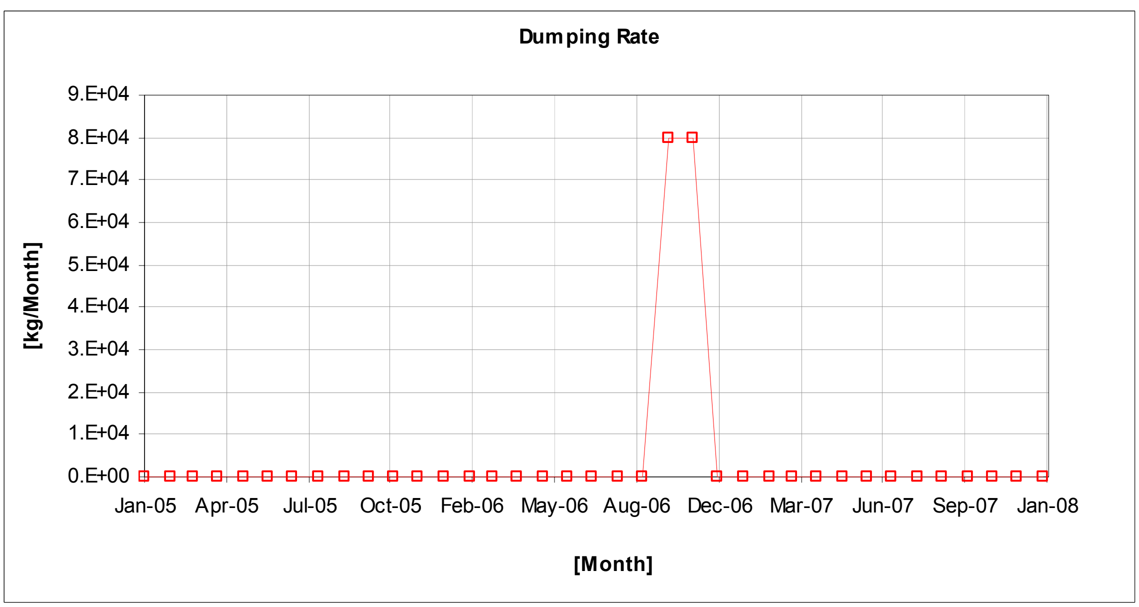

Figure 88: Surge in rate of material being dumped

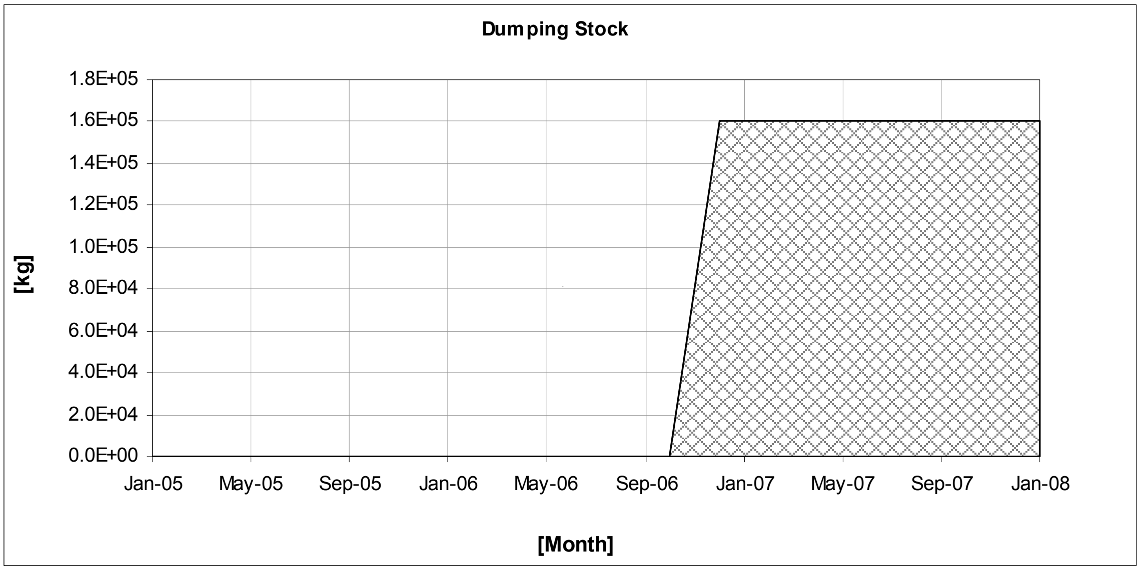

Figure 89: Stock of material dumped due to surge

These feedback loops are a useful illustration of the unintended consequences that a policy decision may have. As illustrated in Section 5.3, a more effective way of reducing the flow of material into the landfill is to promote deconstruction.

6 Discussion of Model, Future Work and Conclusions

This work is briefly summarized and some general principles which are considered relevant for future work are identified.

6.1 Model Analysis

This model hopes to provide insight into the resource consumption issues regarding housing and consider the effects of several policies. One difficulty with analyzing the results of this system is that it can be difficult to identify clearly beneficial strategies or policies, as they are dependent on many parameters and trade-offs. However, this model is useful for quantifying the effects of actions on a large scale, and for illustrating the effects of certain policies. The scale at which this analysis was carried out was considered to be appropriate, as it enabled data from a variety of sources to be combined. However, the accuracy of the model is not known as the macro-scale material or energy flows were not validated against historical data.

6.1.1 Material

The material analysis of residential construction from the house perspective was considered to be accurate, considering the level of detail that it uses (no windows, doors, finishing or appliances). The main difficulty with regard to this analysis was determining the lifespan of the various housing-types. One additional complication was determining whether the individual material's lifespan should be considered or just the lifespan of the structure.

6.1.2 Energy

The detailed analysis of energy consumption of houses in New Orleans illustrated that this methodology is useful for approximating what the energy consumption is on a monthly and yearly basis (see Section 4.6.2.3). This enables future energy consumption patterns to be considered, based on changes to the housing stock in New Orleans. However, the data are not sufficiently accurate where conclusions can be made with regard to the specific benefits resulting from investments in conservation measures. It does concur with the argument that houses of different sizes should have different energy performance levels (Wilson 2005) as the energy efficiency level of homes needs to be considered in the context of the total square footage.

6.1.3 Labor

The amount of labor (and cost of labor) required is the best estimate based on the official data available, but it does not take into account the many informal working arrangements that existed and currently exist, in New Orleans.

6.2 Scenarios

Examining different scenarios provided a means to illustrate what the tradeoffs would be for policy-makers in New Orleans. It is important to consider that there are a large number of parameters that are outside the control of policy makers, which may actually influence the scenarios suggested in an unexpected manner.

It was difficulty to identify what level of complexity and user input is required for a model that simulates the behavior of New Orleans. Reaching a balance between useful quantitative results and developing a qualitative understanding is difficult. Certain feedback loops were included that do not have an empirically defined relationship which introduces uncertainty. This prevents these results from being considered quantitatively yet it is necessary to consider these loops as their behavior can illustrate certain intrinsic properties of the system.

6.3 Systems Dynamics and GIS

It is necessary for cities to start examining their resource consumption in greater detail. Combining resource flows with a GIS is a natural progression so that communities can see the effects of their actions. With regard to energy usage, the behavior of individuals has been shown to change proportionally to the feedback delay times; the shorter the feedback time, the quicker the change in behavior (Wilson 2007). A similar approach could be applied to resource flow information; if this is illustrated at a city level, it could result in citizens or communities changing their behavior. The rapid growth of web-based mapping software which allows user modification, would allow the inhabitants of a city to provide feedback. Examples of community related maps for New Orleans can be seen here[25] and here[26]. The information gathered in this study is illustrated on a Google Map at the site www.nolamaterial.com.

[25] http://thinknola.com/post/editgrid-maps-via-pk-chan/
[26] http://www.scipionus.com/katrina.html

6.4 New Orleans' 'Environmental Action Plan'

Based on work that the author was involved with in New Orleans during the summer of 2006, this project attempted to become closely aligned with the environmental action plan of the city. This analysis aimed to provide quantitative descriptions of the policies that are proposed in this plan. This requires further work, but the intention is to develop model simulations that match the proposed policies and use this to define targets for the city. In addition, these models will be made publicly available via a website so that the citizens of New Orleans are able to experiment with future visions of the city.

6.5 Future Work

The following four areas are identified as areas where further work is needed:

Data Sharing: The first proposed step for future work is to share the data specific to New Orleans, so that residents can become more aware of the resources used by their city.

Indicators: It is necessary to identify a composite indicator so that a measure of the optimal urban performance can be made. Several indicators are discussed in Appendix D, but no one indicator is recommended.

Energy Analysis: The ORM emphasized that one of the priorities of this work was to examine aspects of energy for New Orleans. Although much work was done in the gathering of data, there remains more work that needs to be done with regard to different scenarios and quantifying what the incremental steps should be with a more comprehensive cost/benefit analysis.

Standardizing and Quantifying Causal Loop Diagrams: The development of more standard causal loops for cities would be useful for future work to enable comparisons. Ideally, this information could be incorporated into environmental action plans of cities so that they could provide quantitative benefits of their proposed policies. For future research it is necessary to work on quantifying certain causal relationships in this regard, either through experimentation with various policies to verify their effect, or through more accurate modeling of human behavior. It is very important for policy-makers (or government officials), to have an understanding of an urban system by considering the chains of causality. This can bring about significant change, as departments that work in parallel realize the impact that they have on each other, when they view the effects of their work in this holistic way. This would be of benefit in New Orleans where there are many departments who in parallel without fully appreciating the effect that their actions have on other departments.

6.6 Conclusions

This method of urban analysis is considered to be a useful way of examining cities. Globally, it will be necessary for cities to reduce their ecological footprint so methodologies that assist with this are extremely important. Based on the predictions of a global population of 9 billion (UN 2004), to ensure the long-term sustainability of humans, we will need to dramatically reduce our resource consumption. By developing a model structure that represents the urban metabolism, and identifying where leverage points exist in a system, this will be an essential approach for examining how policy makers can effectively intervene in a system, with the result of more resource efficient cities.

Appendices

All models and data are currently available here:

http://web.mit.edu/djq/Public/NO/

The author can be contacted here:

djq [at] mit.edu

Appendix A - System Dynamics Model

A.1 Categories of Typical Dynamic Behavior Patterns

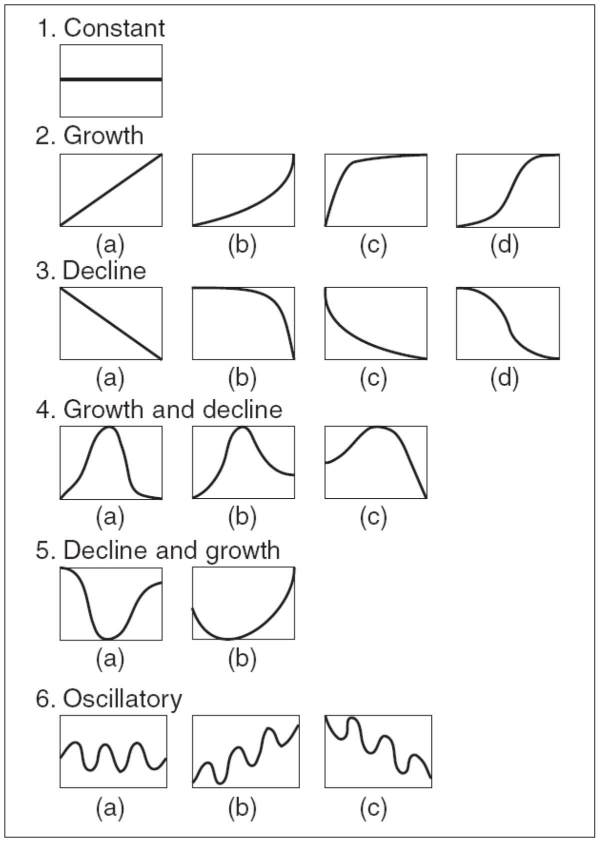

Figure 90: Categories of basic dynamic behavior patterns observed in systemic feedback problems
(Barlas 2002)

A.2 Coefficient of Variation of the Root Mean Square Error

$$CVRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{n-p}}}{\bar{y}} x100$$

y_i The measured data point

$\hat{y}_i$ The simulated data point

$\bar{y}$ The average of the measured data points

n The number of data points in the series

p The number of independent variables, equal to 1 for calibrated simulations

A.3 Equations for SD Models

Equations for model in Figure 19:
Figure 19: Model structure illustrating delays in relation to permits and construction

(Model constructed using Vensim PLE)

(01) Construction=Houses Under Construction/Time to Construct
Units: Houses/Month

(02) Construction Started=Permits Generating Construction*Permit to House Convertor
Units: Houses/Month

(03) Demand for Demolition=IF THEN ELSE(Houses destroyed by Hurricane>100, Demolition Demand, 0)
Units: Permits/Month

(04) Demand for Reconstruction=IF THEN ELSE(Houses destroyed by Hurricane>100, Reconstruction Demand, 0)
Units: Permits/Month

(05) Demolition=Permits to Demolish Houses/Time to process Permit
Units: Permits/Month

(06) Demolition Demand=9398
Units: Permits/Month

(07) Demolition Permits=Permits required to Demolish/Response Time of Residents
Units: Permits/Month

(08) Destroyed Housing= INTEG (Houses destroyed by Hurricane, 0)
Units: Houses

(09) FINAL TIME = 30
Units: Month (*The final time for the simulation.)*

(10) Houses destroyed by Hurricane=Hurricane
Units: Houses/Month

(11) Houses Under Construction= INTEG (Construction Started-Construction, 0)
Units: Houses

(12) Housing Stock= INTEG (Construction-Houses destroyed by Hurricane, 198232)
Units: Houses

(13) Hurricane= (Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)
Units: Houses/Month

(14) INITIAL TIME = 0
Units: Month (*The initial time for the simulation.)*

(15) Permit to House Convertor=1
Units: Houses/Permits

(16) Permits being Processed=Permits Required to Reconstruct/Response Time of Residents
Units: Permits/Month

(17) Permits Generating Construction=Permits to Reconstruct Houses/Time to process Permit
Units: Permits/Month

(18) Permits Processed for House Demolition= INTEG (Demolition, 0)
Units: Permits

(19) Permits Processed for House Reconstruction= INTEG (Permits Generating Construction, 0)
Units: Permits

(20) Permits required to Demolish= INTEG (Demand for Demolition-Demolition Permits, 0)
Units: Permits [0,?]

(21) Permits Required to Reconstruct= INTEG (Demand for Reconstruction-Permits being Processed, 0)
Units: Permits [0,?]

(22) Permits to Demolish Houses= INTEG (Demolition Permits-Demolition,1)
Units: Permits

(23) Permits to Reconstruct Houses= INTEG (Permits being Processed-Permits Generating Construction,0)
Units: Permits

(24) Pulse Quantity=105323
Units: Houses *(The quantity added to the input at the pulse time.)*

(25) Pulse Time=8
Units: Month *(The time at which the pulse increase in the input occurs.)*

(26) Reconstruction Demand=55011
Units: Permits/Month

(27) Response Time of Residents=9
Units: Month

(28) SAVEPER = TIME STEP
Units: Month [0,?] *(The frequency with which output is stored.)*

(29) TIME STEP = 1
Units: Month [0,?] *(The time step for the simulation.)*

(30) Time to Construct=6.5
Units: Month

(31) Time to process Permit=1.3
Units: Month

Equations for Figure 25: Employment as a result of housing demand

(Model constructed using Vensim PLE)

(02)	Demand for Employees= (Reconstruction Demand-Worker Demand)/Time to adjust	
(03)	Employment Delay=	4.5
(04)	Excess Workers=	Construction
(05)	FINAL TIME =	100
(06)	INITIAL TIME =	0
(07)	Reconstruction Demand=	55011
(08)	SAVEPER =	TIME STEP
(09)	TIME STEP =	1
(10)	Time to adjust=	3.5
(11)	Worker Demand=	INTEG (Workers-Excess Workers, 20000)
(12)	Workers=	Workers in Transit/Employment Delay
(13)	Workers in Transit= INTEG (Workers seeking employment-Workers,0)	
(14)	Workers seeking employment=	Demand for Employees

Equations for Figure 53: Driving equation for city (similar to Figure 19) with the addition of *New Construction* and *End of Life Rate*

(Model constructed using Stella)
New Construction = End_of_Life_Rate+Increase

End of Life Rate = IF(Lifespan=0) THEN (0) ELSE(Housing_Stock/Lifespan)

Equations for Figure 54, Figure 67, Figure 69, Figure 73, Figure 86 are not described here in detail. The reader is recommended to visit http://web.mit.edu/djq/Public/NO/ where the models can be downloaded. In addition all equations are listed in a text file so that they can be rebuilt using a different software program if desired.

Figure 54: Flows of material driven by the model shown in Figure 53

Figure 67: Energy required at various phases of a house's lifetime

Figure 69: Labor required at various phases of the houses lifetime

Figure 73: Schematic for Investment in Conservation (loop shown in green)

Figure 86: Material flows considering the interaction between landfill and dumping

A.4 Input File

Variable Name												Units
	Material	PRE-USE										
	Abiotic	Biotic	Water	Air	Total							
Rucksack Factor	0.41	5.51	34.92	0.08	40.92	Lumber						kg/kg
...	1.24	0.00	8.71	0.04	9.99	Concrete						kg/kg
...	9.32	0.00	81.90	0.77	91.99	Steel						kg/kg
...	0.54	0.00	111.33	0.34	112.21	OSB						kg/kg
...	1.40	0.00	33.79	0.02	35.21	Gypsum						kg/kg
...	2.60	0.00	6.61	0.00	9.21	Asphalt						kg/kg
...	3.37	0.00	373.10	0.25	376.72	Vinyl						kg/kg
...	6.22	0.00	94.50	2.09	102.81	Fiberglass						kg/kg
...	2.49	0.00	122.20	1.62	126.31	Building Paper						kg/kg
...	2.51	0.00	15.00	0.26	17.77	AAC						kg/kg
	Lumber	Concrete	Steel	OSB	Gypsum	Asphalt	Vinyl	Fiberglass	Building Paper	AAC		
Material Convertor	12939.58	22000.00	0.00	7241.53	7397.73	2215.09	2168.59	226.06	154.90	0.00	Wood Housing	kg/house
...	0.00	22000.00	1192.31	7241.53	7397.73	2215.09	2168.59	226.06	154.90	0.00	Steel	kg/house
...	11578.19	22000.00	0.00	5226.94	7397.73	2215.09	105.72	0.00	158.22	32233.45	AAC	kg/house
...	10127.79	22000.00	0.00	8018.60	7397.73	2215.09	2168.59	105.72	154.90	0.00	SIP	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	RC	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	SCIP	kg/house
Material Refurbish Convertor	0.00	0.00	0.00	7241.53	7397.73	2215.09	2168.59	226.06	154.90	0.00	Wood Housing	kg/house
...	0.00	0.00	0.00	7241.53	7397.73	2215.09	2168.59	226.06	154.90	0.00	Steel	kg/house
...	0.00	0.00	0.00	5226.94	7397.73	2215.09	105.72	0.00	158.22	0.00	AAC	kg/house
...	0.00	0.00	0.00	8018.60	7397.73	2215.09	2168.59	105.72	154.90	0.00	SIP	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	RC	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	SCIP	kg/house
Material in Structure	12939.58	22000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Wood Housing	kg/house
...	0.00	22000.00	1192.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Steel	kg/house
...	11578.19	22000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	32233.45	AAC	kg/house
...	10127.79	22000.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	SIP	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	RC	kg/house
...	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	SCIP	kg/house
	Material	USE										
	Material	POSTUSE										
Waste Convertor	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074		kg/kg
	Energy	PRE-USE										
Direct Embodied Energy Convertor	2.50	1.30	32.00	8.00	6.10	9.00	50.20	30.30	37.70	3.60		MJ/kg
Construction and Transportation Energy Convertor	1858.00	1858.00	1858.00	1858.00	1858.00	1858.00						MJ/house
	Energy	USE										
Energy per House	3555.00	3555.00										kWh/month
Energy Cost	0.098											$/kWh
	Energy	POSTUSE										
Demolition Energy Convertor	7000.00	7000.00	7000.00	7000.00	7000.00	7000.00						MJ/house
Deconstruction Energy Convertor	10000.00	10000.00	10000.00	10000.00	10000.00	10000.00						MJ/house
	Labor	PRE-USE										
Labor Hours Construction	805.45	933.40	754.20	619.40	0.00	0.00						hr/house
Labor Hours Refurbishment	333.60	222.20	198.20	618.00	0.00	0.00						hr/house
POSTUSE Labor Deconstruction	320.00											hr/house
POSTUSE Labor Demolition	31.00											hr/house
	Labor	USE										
Labor Cost	12.00	12.00	12.00	12.00	12.00	12.00						$/sq ft
	Labor	POSTUSE										
POSTUSE Cost Deconstruction	12.00											
POSTUSE Cost Demolition	5.00											
	General Parameters											
Effectiveness	0.70	1.00	1.00	0.00	0.50	0.30	0.00	0.00	0.00	1.00		%

Appendix B - Housing Data

B.1 Housing in Target Areas

Target Areas Examined:

- Lower 9th Ward
- St. Bernard at N. Claiborne Ave
- S. Claiborne Avenue at Toledano
- Harrison Avenue
- Gentilly Boulevard at Elysian Fields
- Broad St at Lafitte Greenway
- Carrolton Avenue
- New Orleans East Plaza (no residential houses identified)

B.2 Wooden structures by Census Block

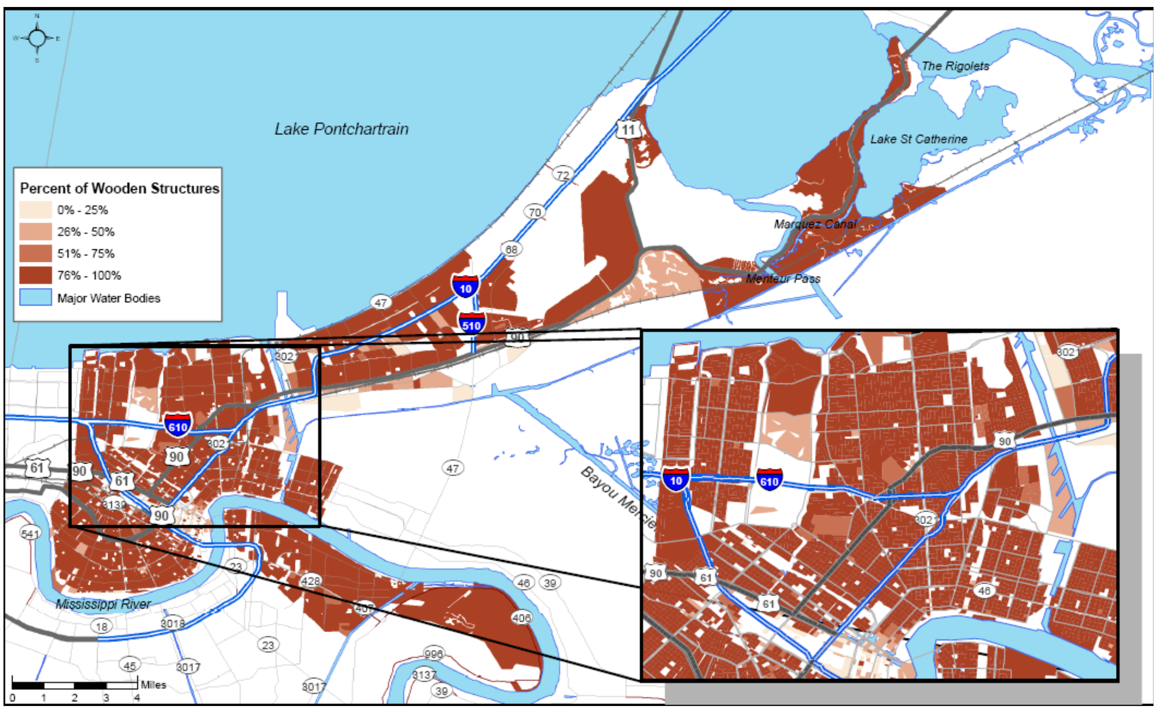

Figure 91: Wooden structures by census block (LSU GIS Clearinghouse, 2008)

Appendix C - Energy Data

C.1 Theoretical and Actual Energy consumption Data

The following figures show the energy consumption for all ten house types with three levels of energy performance (high, medium and low).

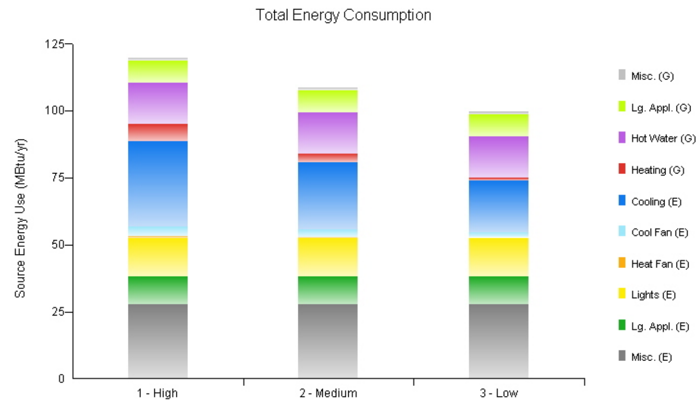

Figure 92: House 1 – Total Energy Consumption

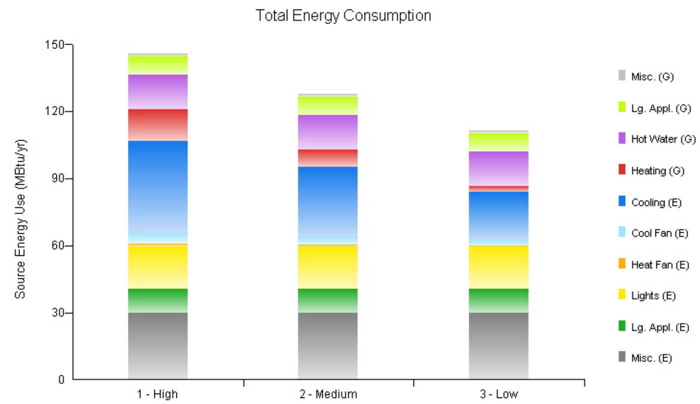

Figure 93: House 2 – Total Energy Consumption

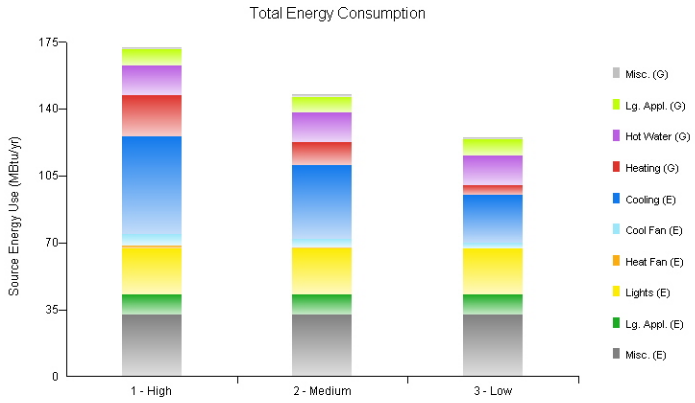

Figure 94: House 3 – Total Energy Consumption

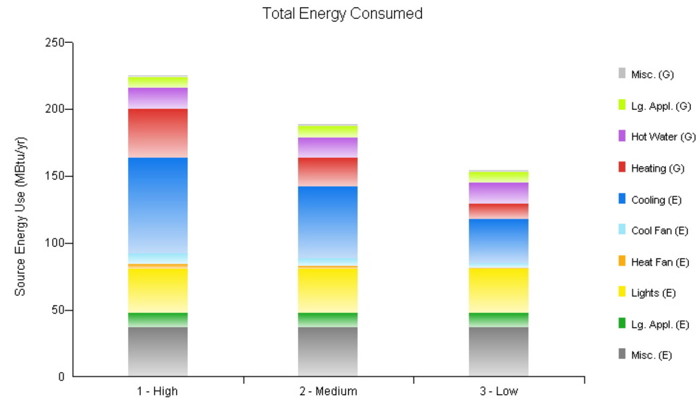

Figure 96: House 5 – Total Energy Consumption

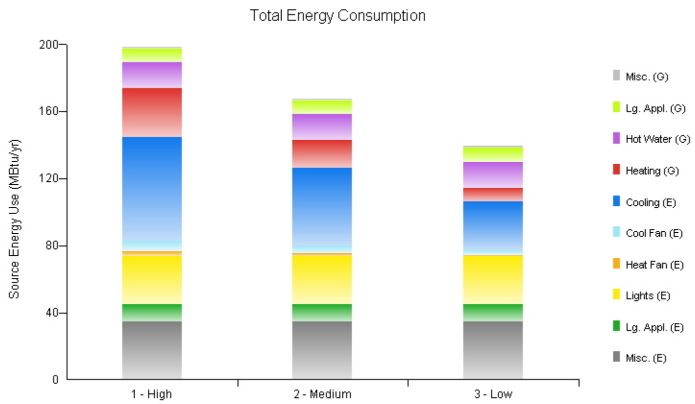

Figure 95: House 4 – Total Energy Consumption

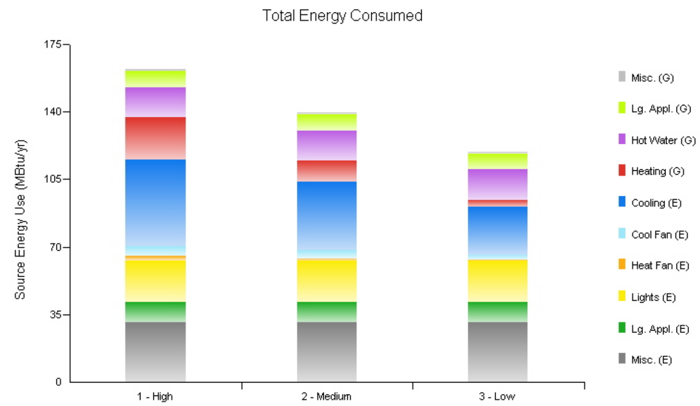

Figure 97: House 6 – Total Energy Consumption

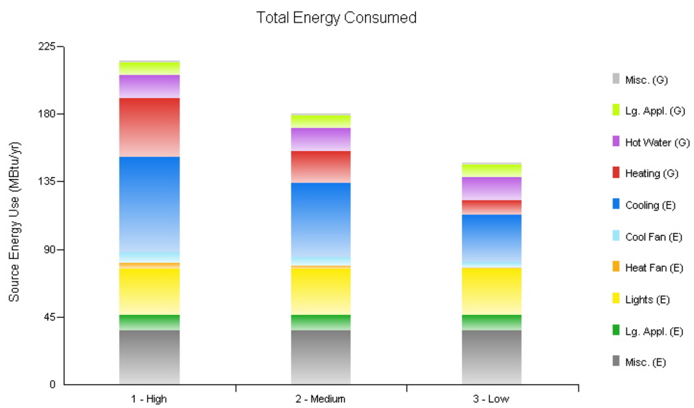

Figure 98: House 7 – Total Energy Consumption

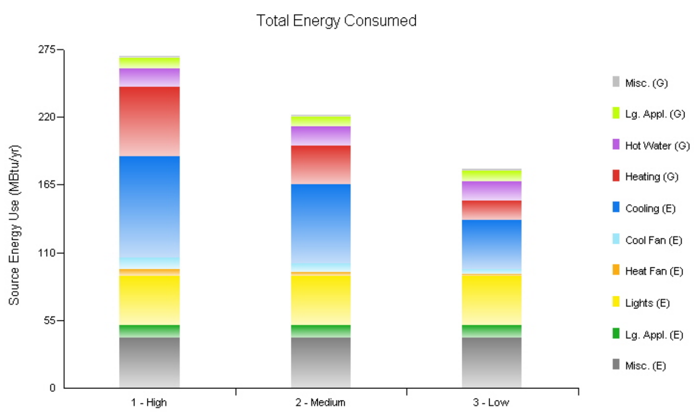

Figure 99: House 8 – Total Energy Consumption

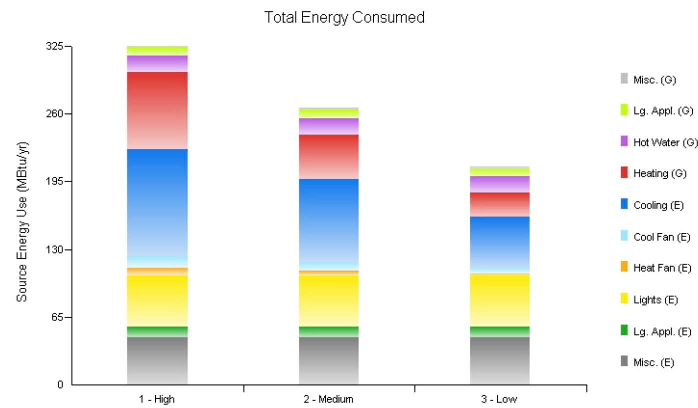

Figure 100: House 9 – Total Energy Consumption

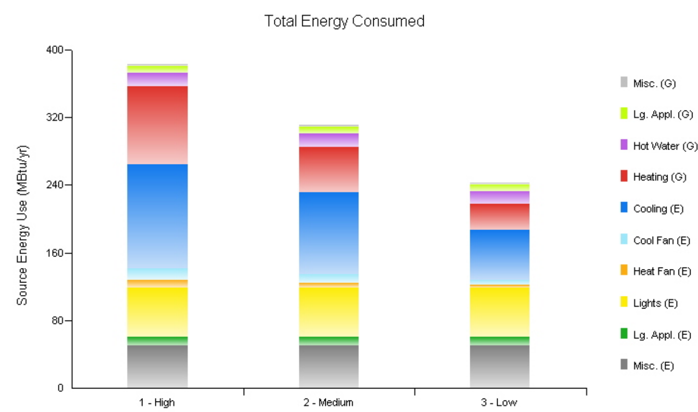

Figure 101: House 10 – Total Energy Consumption

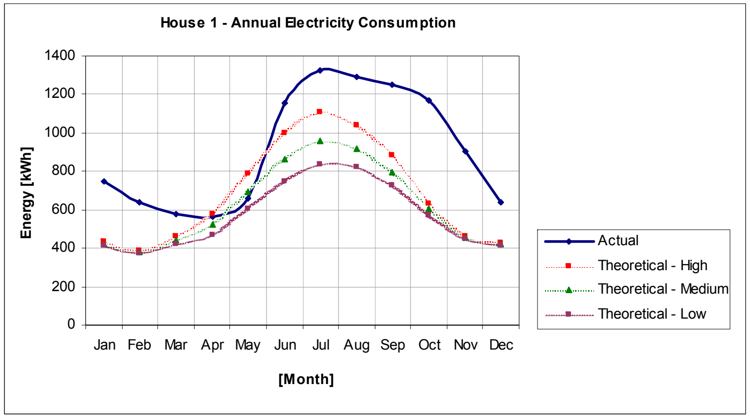

Figure 102: House 1 – Monthly Electricity Consumption

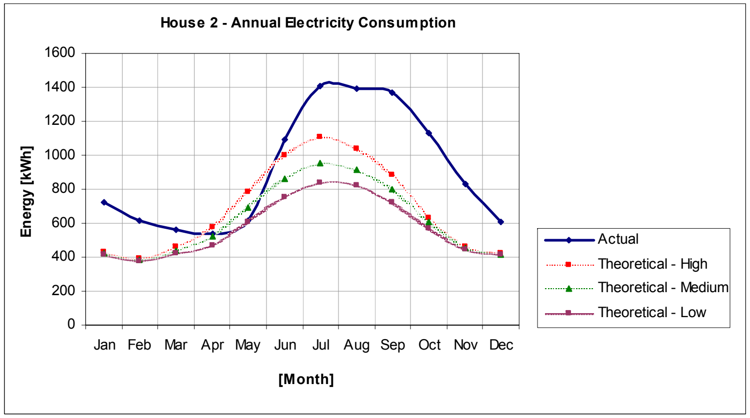

Figure 104: House 2 – Monthly Electricity Consumption

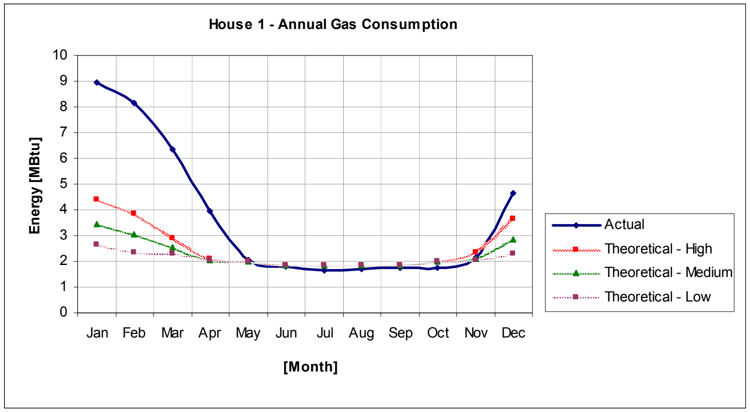

Figure 103: House 1 – Monthly Gas Consumption

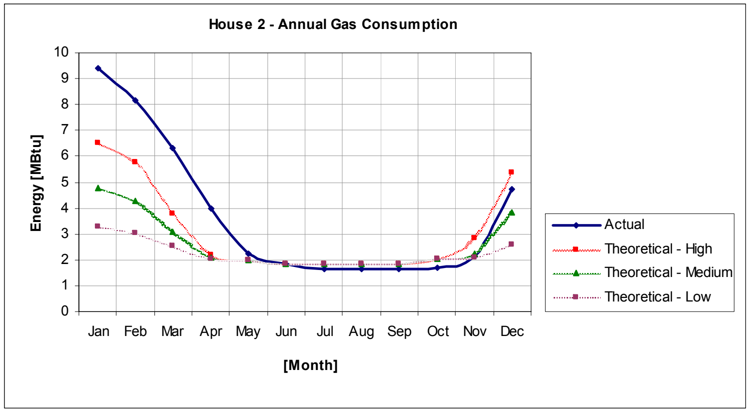

Figure 105: House 2 – Monthly Gas Consumption

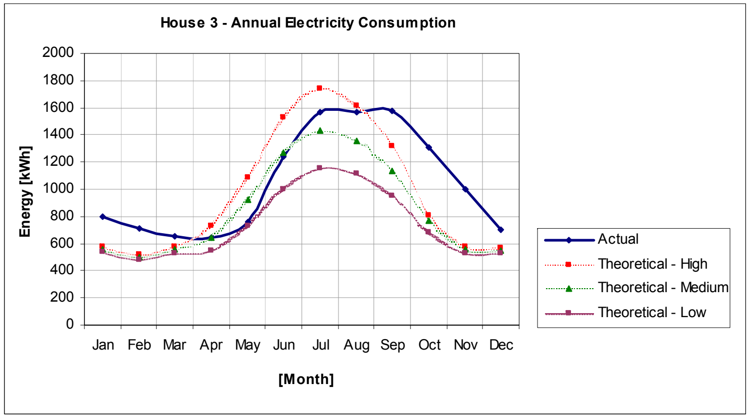

Figure 106: House 3 – Monthly Electricity Consumption

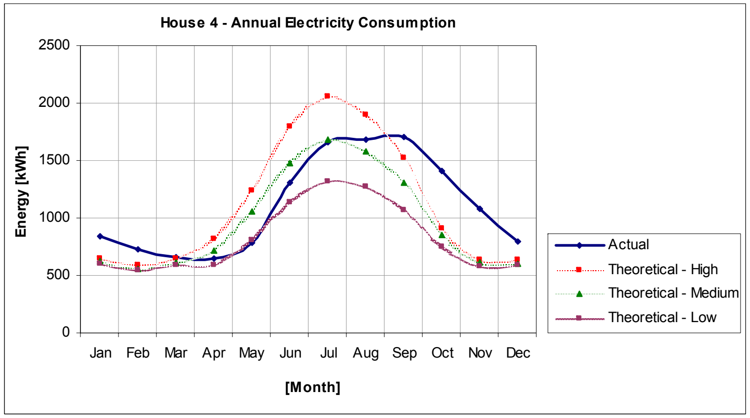

Figure 108: House 4 – Monthly Electricity Consumption

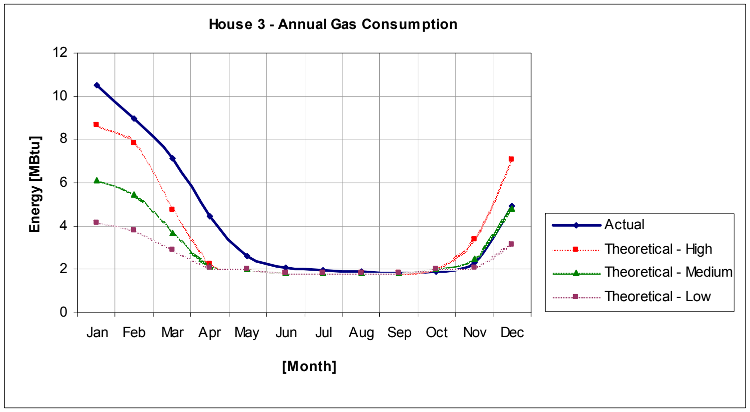

Figure 107: House 3 – Monthly Gas Consumption

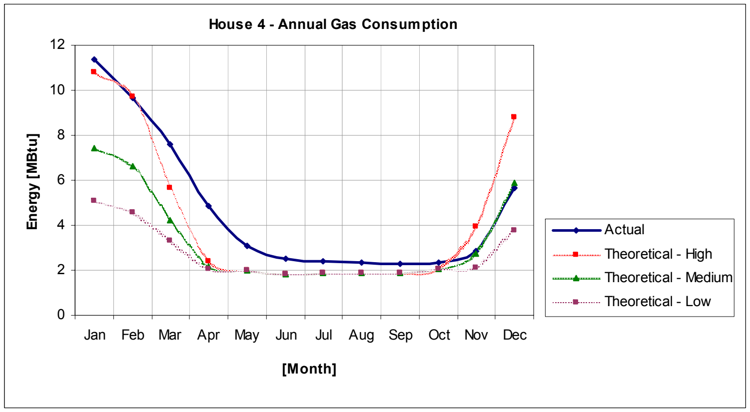

Figure 109: House 4 – Monthly Gas Consumption

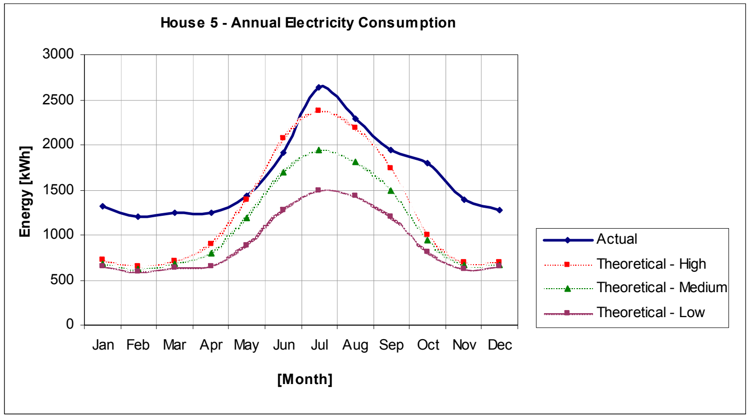

Figure 110: House 5 – Monthly Electricity Consumption

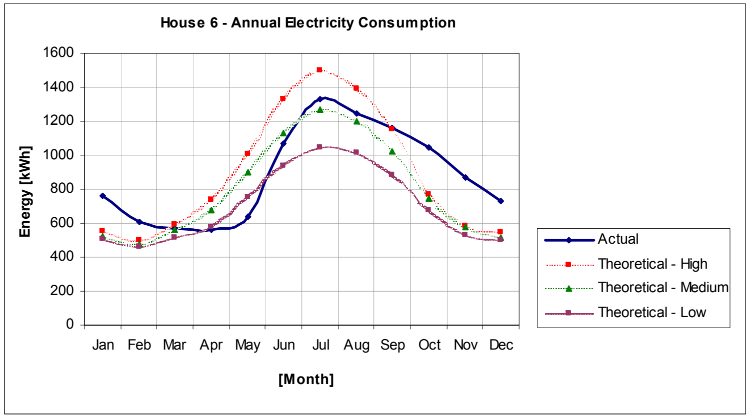

Figure 112: House 6 – Monthly Electricity Consumption

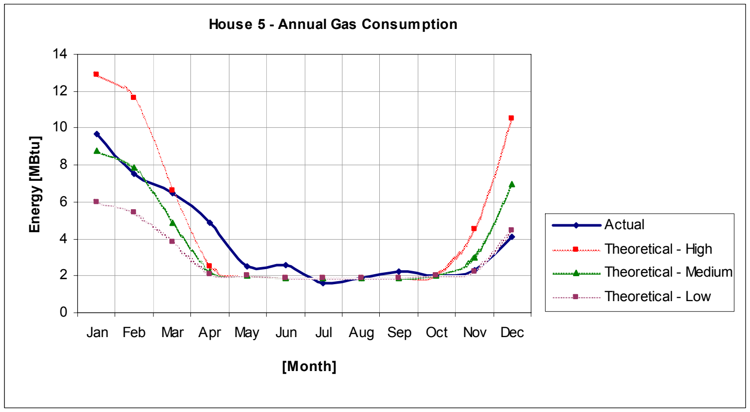

Figure 111: House 5 – Monthly Gas Consumption

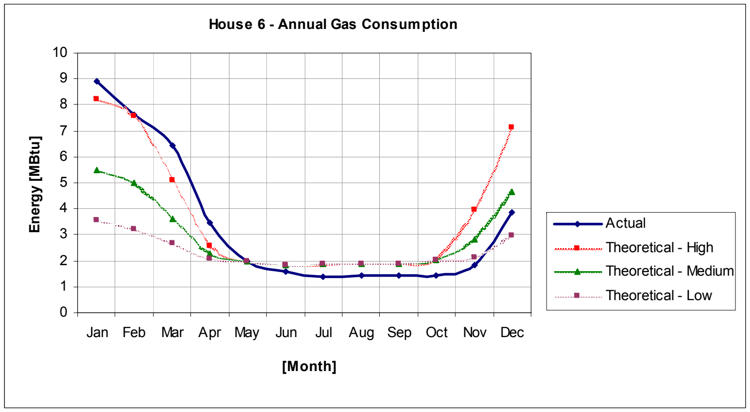

Figure 113: House 6 – Monthly Gas Consumption

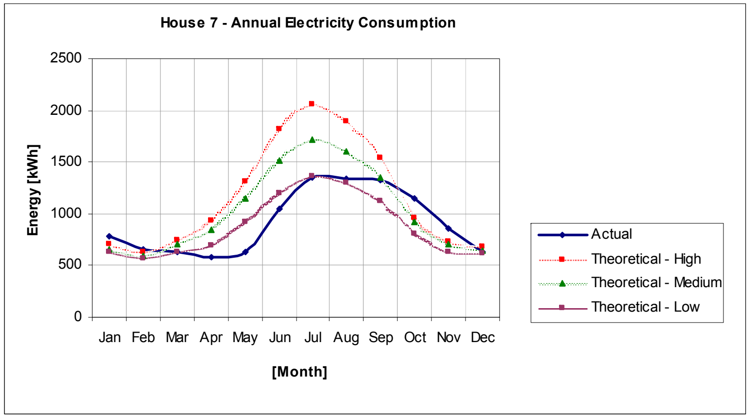

Figure 114: House 7 – Monthly Electricity Consumption

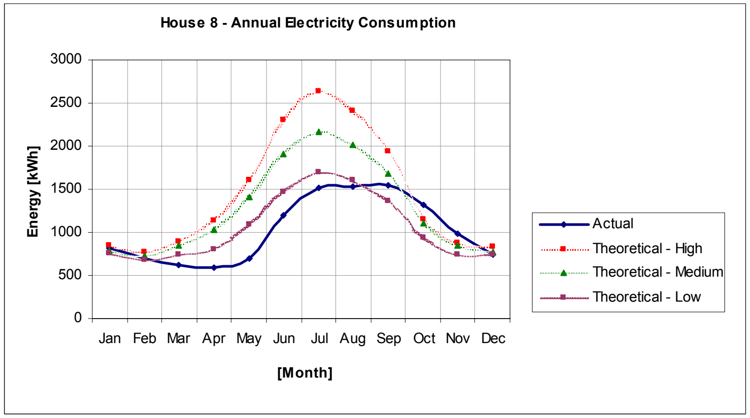

Figure 116: House 8 – Monthly Electricity Consumption

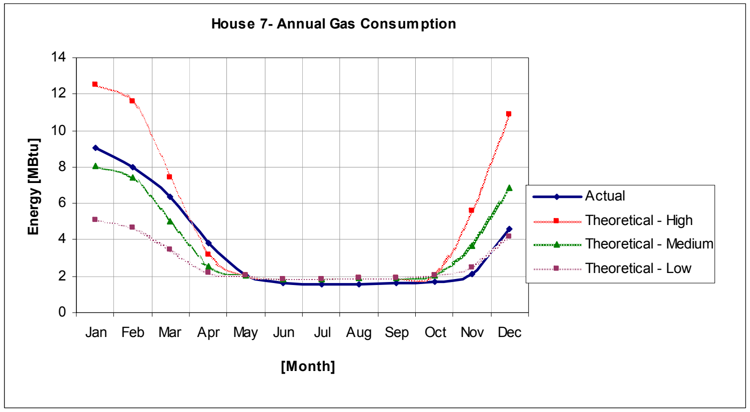

Figure 115: House 7 – Monthly Gas Consumption

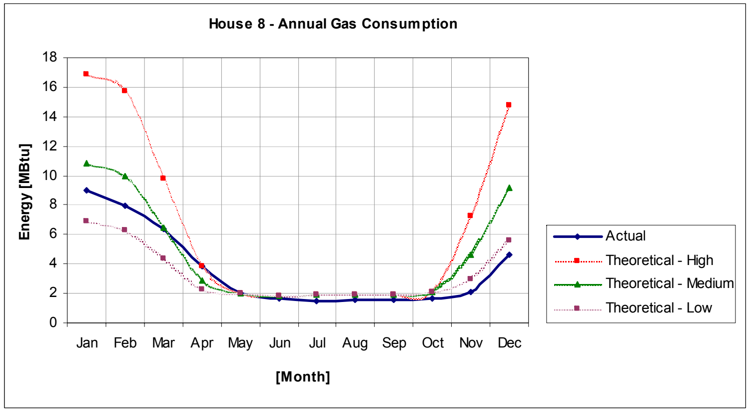

Figure 117: House 8 – Monthly Gas Consumption

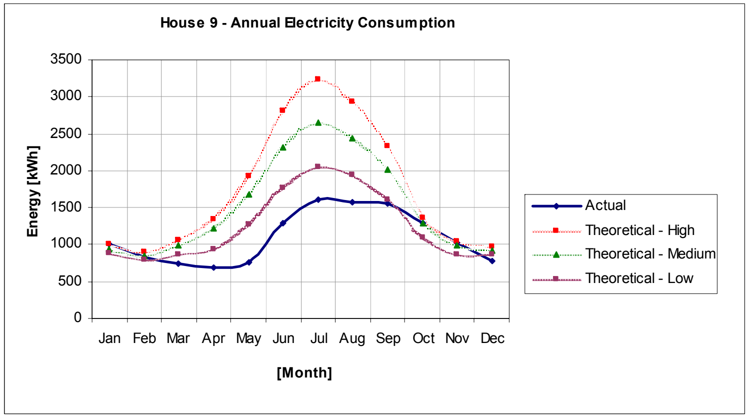

Figure 118: House 9 – Monthly Electricity Consumption

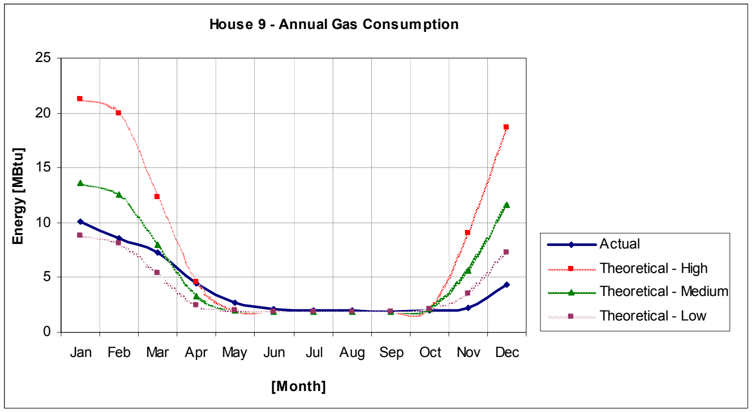

Figure 119: House 9 – Monthly Gas Consumption

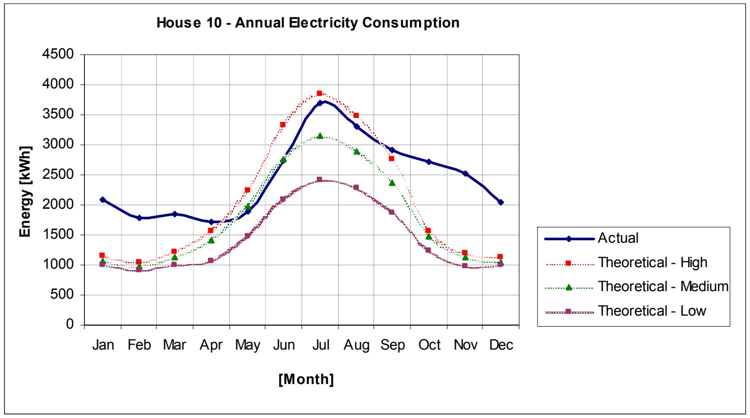

Figure 120: House 10 – Monthly Electricity Consumption

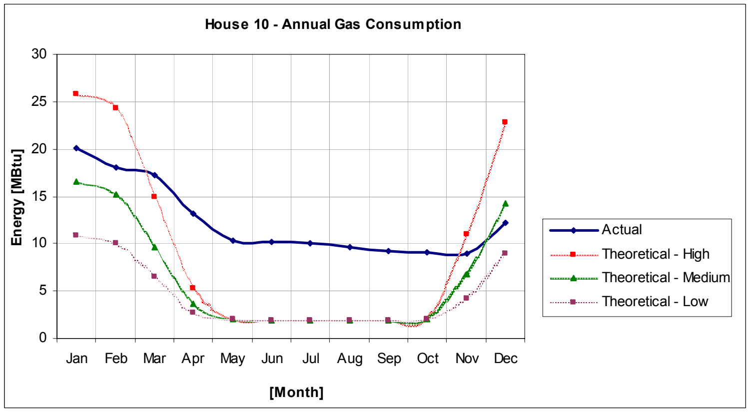

Figure 121: House 10 – Monthly Gas Consumption

Appendix D – Indicators and Metrics

The following indicators are considered to be relevant for urban analysis and are briefly described. These are Life-Cycle Analysis, the Ecological Footprint, Material Intensity, and Material Intensity per Unit of Service. It is proposed that a combination of these should be used to develop a composite indicator to illustrate the optimal urban performance.

A key aspect of this analysis is developing a methodology to estimate the lifespan of houses, based on the construction method. Hardin (1968) describes the difficulties of using implicit assumptions when defining metrics in the article, "The Tragedy of the Commons". Hardin states, "It is when the hidden decisions are made explicit that the arguments begin. The problem for the years ahead is to work out an acceptable theory of weighting". In this case, the most important factor is the lifespan of the structure which is difficult to define.

D.1 Lifespan of Houses

There are two main factors to consider regarding to the lifespan of houses. The first is concerned with the structural/design life of the material; the second is concerned with external factors that affect the house's lifespan. The first factor can be controlled by virtue of the materials selected, while the second is dependent on economics, the local environment, obsolescence and the needs of the occupants. In this study there is no rigorous way of controlling the second parameter. According to research which analyzes the lifespan of buildings, "there is no significant relationship between the structural system and the actual useful life of the building" (O'Connor 2004). This study focuses solely on the structural/design life of the material, where this information is available.

Using the Building for Environmental and Economic Sustainability lifecycle analysis tool (BEES 2007), estimates of the lifespan of houses constructed using a variety of materials were made. BEES data are organized in a software tool developed by the US National Institute of Standards and Technology (NIST). This data does not take into account local climate conditions and how it affects the lifespan of the structure, which is of significance in New Orleans with its warm and humid climate. For this reason, a scaling factor is proposed based on the percentage of organic material present, which would be used to adjust the expected lifespan of the housing material in New Orleans. The three major categories that need to be considered are the percentage of organic material, the damage caused by exposure to water and the effect of termites on the material. With a lack of empirical data this is difficult to estimate but values for the lifespan of housing and scaling factors are proposed in the following table (Table 19). One difficulty with the analysis of newly developed construction materials, such as SIPs, is that they have not existed for a sufficiently long time period so that their behavior can be known after 75 years.

Table 19: Lifespan and fraction of organic material in structure (BEES 2007)

	Lifespan	**Fraction Organic Material**
	[years]	[-]
Wood Stud	75	0.51
Steel Stud	75	0.34
AAC	100	0.30
SIP	75	0.49

D.2 Life-Cycle Analysis (LCA)

A LCA attempts to include all known environmental impacts that result from an activity. This assessment should cover all stages in the life of a product, material or service. It should aim to quantify all physical exchanges of a product or material's system, and identify any transfer of impacts from one medium to another. Defining the spatial and temporal boundaries of the system analyzed is a critical aspect of the analysis as interactions with other connected systems must be decided. Figure 122, Figure 123 and Figure 124 illustrate the materials, energy and labor for a wood-stud house in New Orleans with a lifespan of 75 years.

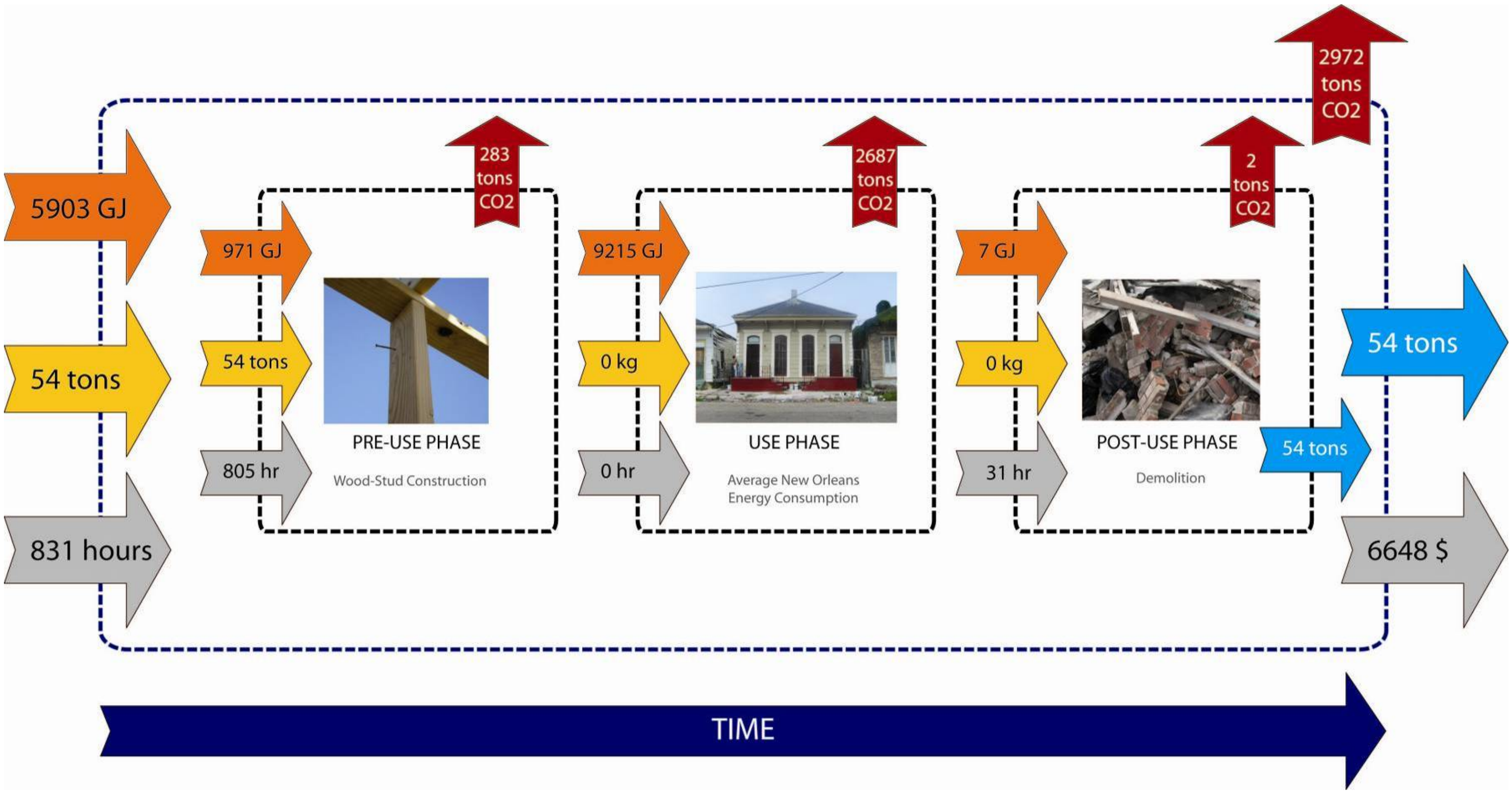

Figure 122: Material, energy and labor used during life cycle of house

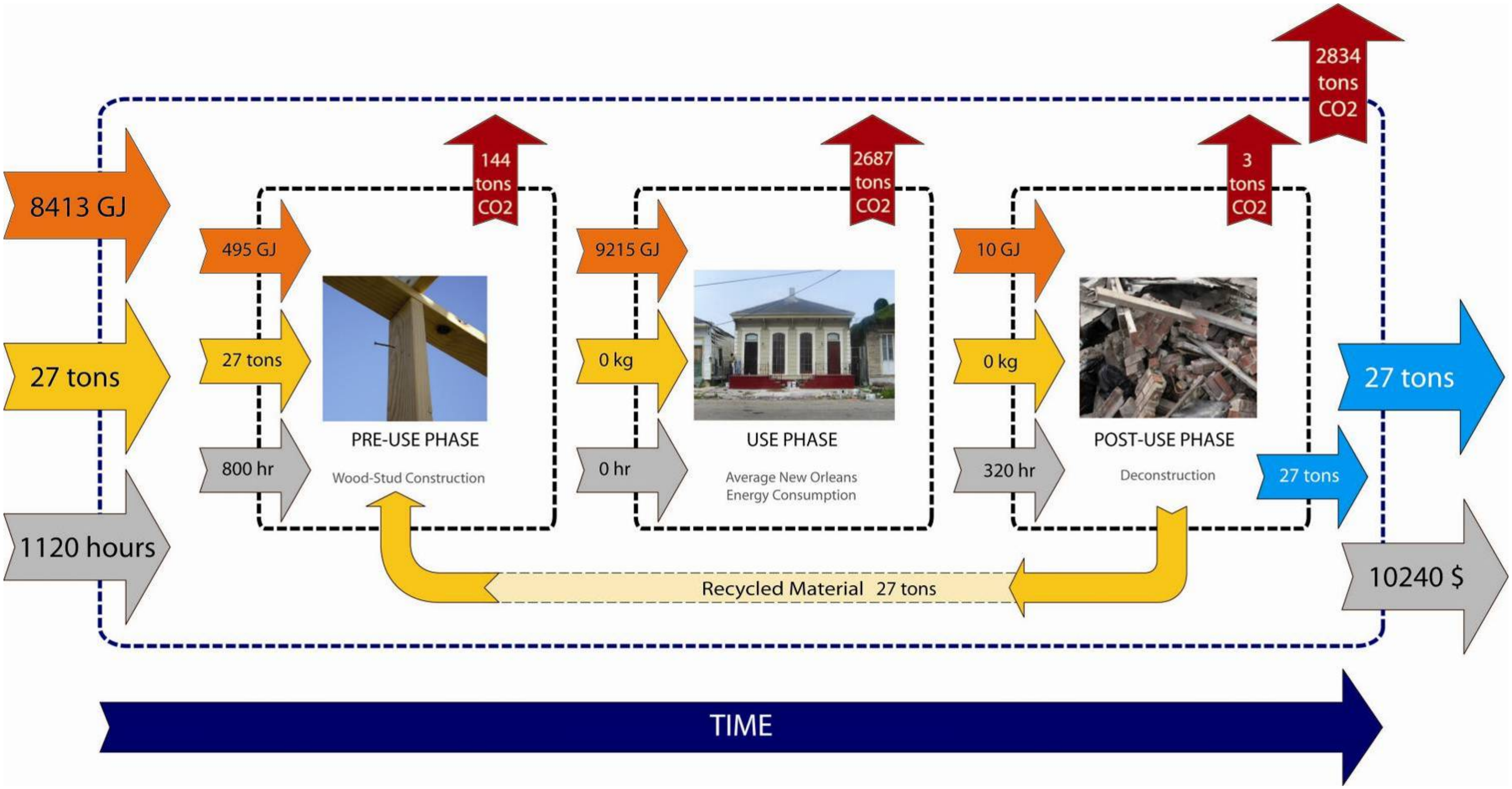

Figure 123: Material, energy and labor used during life cycle of house with deconstruction

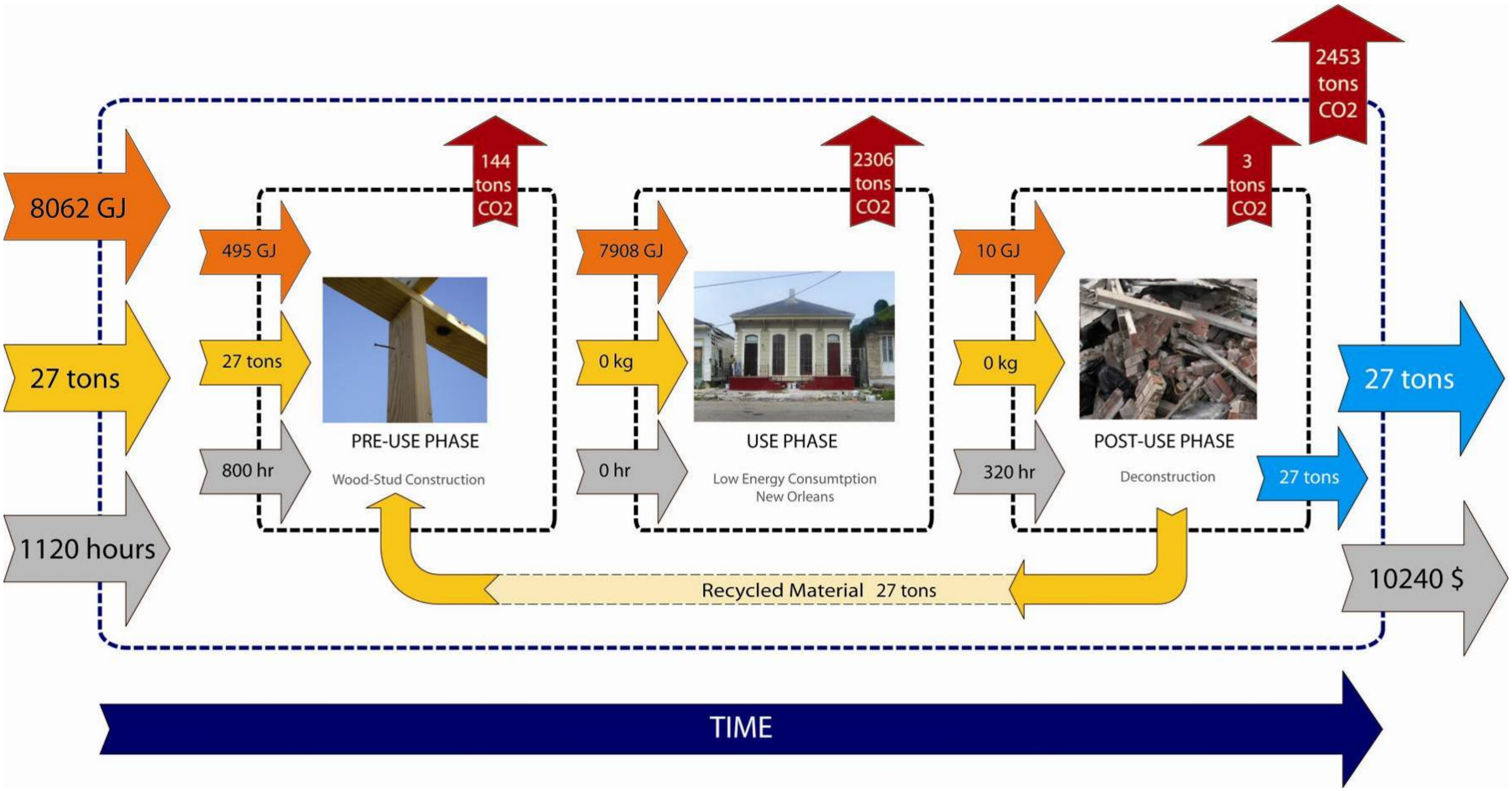

Figure 124: Material, energy and labor used during life cycle of a low-energy house with deconstruction

D.3 The Ecological Footprint

The ecological footprint is defined by Reese and Waskernagel (1996) as "the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced by a defined population". This methodology is used to estimate how human resource consumption fits at a global level and can be used for individuals to estimate their environmental burden on the world[27]. While this can be used to estimate what productive land area a city requires to sustain itself, the concept is most useful when considering global resource consumption. Several cities have analyzed their resource consumption in this way with results for London City at 293 times the area of London.[28]

Another interesting measure that links energy consumption to land area is shown in Figure 125 This map is shows the carbon[29] produced due to energy consumption for the year of 2004[30] per area (each cell is 100 x 100 km).

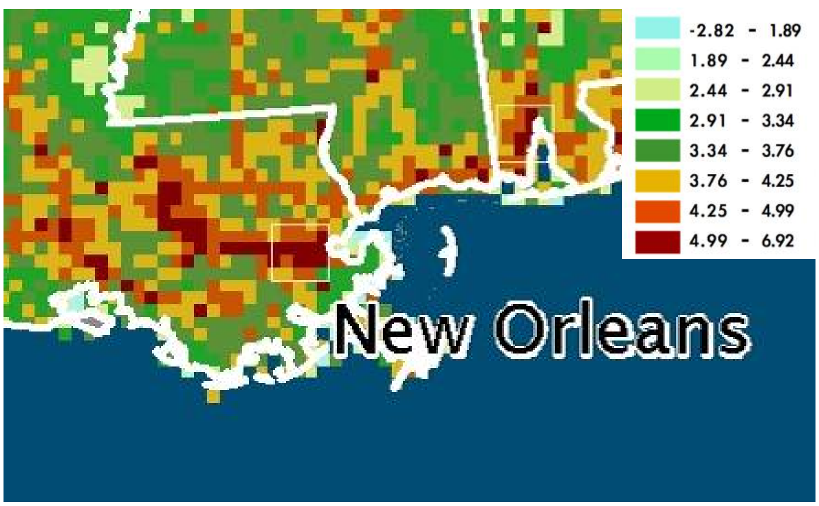

Figure 125: Illustration of CO^2 production per unit area of New Orleans in 2004

[27] http://www.footprintnetwork.org/
[28] http://www.london.gov.uk/mayor/sustainable-development/susdevcomm_footprint.jsp
[29] Units are log_{10} million metric tons of carbon/gridcell/year
[30] http://www.purdue.edu/eas/carbon/vulcan/images/Vulcan.total.grid.cities.legend.2.jpg

D.4 Material Intensity (or Ecological Rucksack)

The concept of 'Material Intensity[31]', also referred to as an 'Ecological Rucksack', was developed by Schmidt-Bleek and his colleagues in the Wuppertal Institute, Germany (Schmidt Bleek 1994). The 'Material Intensity' (MI) concept considers the total quantity (in kg) of all natural materials that are used or disturbed from their natural state and views this total as the input required to produce a product (Schmidt-Bleek 1994). Schmidt-Bleek considered this to be an appropriate method of approximating the level of environmental stress created by the product, when the product is considered from the cradle to the point of use. All materials used in the production of goods are listed by weight and multiplied by rucksack factors, and then summed to include all materials.

$$MI = \Sigma\, (m_i \bullet R_i)$$

MI = Material Intensity [kg]

m = mass of material in product [kg]

R = Rucksack Factor [no units]

Ecological rucksack values for virgin materials are listed in Figure 126. This method of analysis is useful for preliminary estimates of the environmental impact of products, but does not take into account the resulting toxicity of material flows. In this study, it is assumed that the MI factor for recycled materials is 1 kg/kg. This measure considers the air, water, biotic[32] and abiotic[33] materials required for producing 1 kg of a material.

[31] 'Material Intensity' and 'Material Input' are used interchangeable in existing literature.

[32] Biotic resources are renewable resources

[33] Abiotic resources are non-renewable natural resources

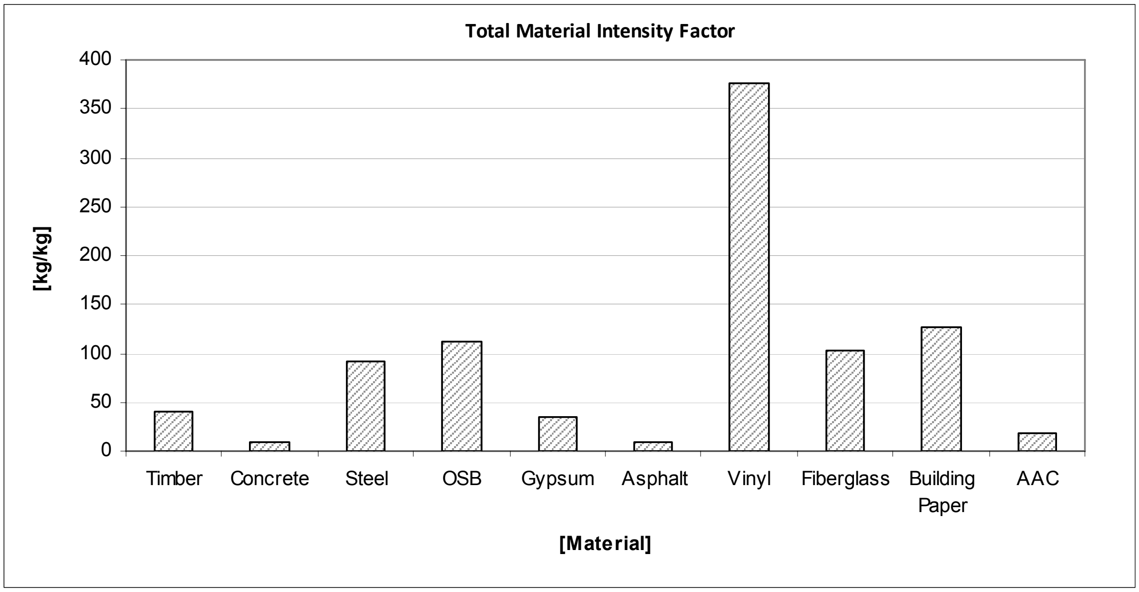

Figure 126: Total Material Intensity factor

D.5 Material Input Per unit Service (MIPS)

Material Intensity per unit service is a measure of the environmental stress intensity with respect to the entire product life. Expressed as an equation, MIPS is as follows:

MIPS=MI/S

MI = Material Intensity [kg]

S = Service Unit

In this study, the service unit of a house is the floor area that is available to its inhabitants over a defined time period. The service unit used in the MIPS calculations for houses in New Orleans was selected as 'the net floor area (m^2)/the service life of the building in years'. The average number of inhabitants per house was not considered. The service life of the house was selected for the service unit calculation as it is a useful indicator of the amount of service that is produced by the building: the longer a building lasts, the more service it provides. The assumption made in these calculations was that the 'Use' phase of the house would be as many years as the material-system could survive. For the service unit measure to be consistent when comparing different construction types, the perimeter/floor area ratio of the building needs to be the same, as this, affects the amount of service provided. This indicator is a useful way of combining environmental stresses that a house causes over the three phases of 'Pre-Use', 'Use' and 'Post-Use'.

D.6 Calculating MIPS values for Different Housing Systems

Calculation of the MIs of the building components in this study took into account only the materials present within the components, and their amounts were multiplied by the MI factor for each material. This allows a relatively quick and reliable calculation of the MI for the buildings. The calculation did not examine the full life cycle process chains of specific materials, (which would include the material and energy inputs and transportation) but only the material composition of the finished product. General assumptions were made with regard to the transportation and surplus building materials due to onsite waste (Section 4.5.1). Waste material consists of the amount of materials that remains unused after construction is completed.

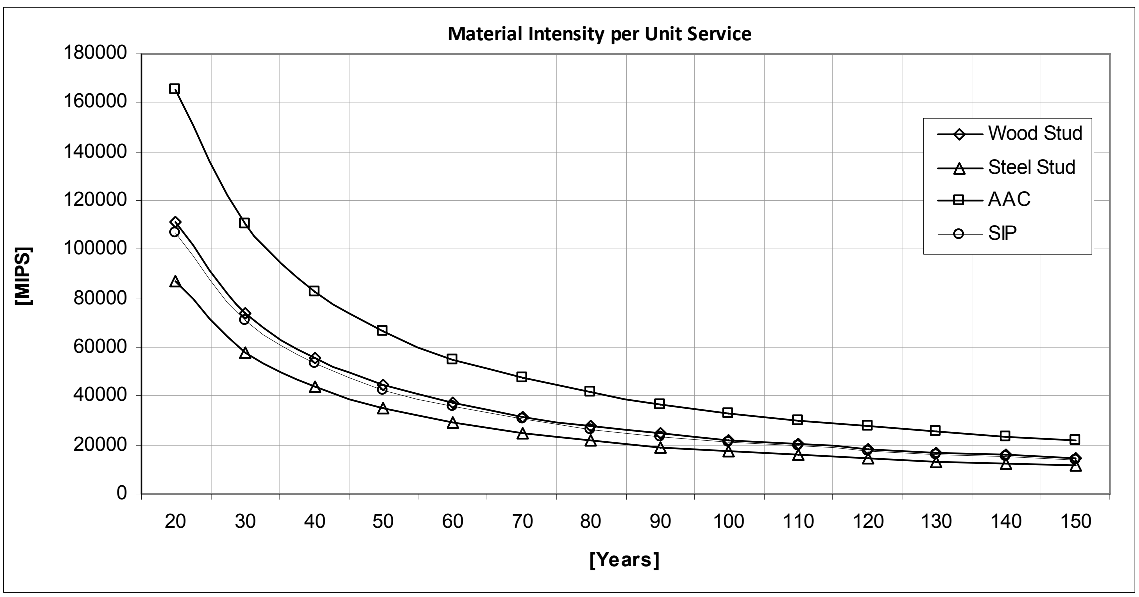

Figure 127: MIPS calculation for 2000 sq ft house

D.7 Labor/ Work Force Development Potential

Another proposed metric, which was not fully explored in this study, was the 'Work Force Development Potential'. This measure could examine the number of labor hours provided by each housing system. The more labor intensive the construction, demolition or deconstruction process is, the higher this indicator is. In addition, it was proposed to weight the development of transferable construction skills more highly. An example of this would be construction using steel studs which is also used for commercial premises.

D.8 Composite Indicators

This model started to examine distinct parts of a city that require resources for housing and attempted to link them together. One difficulty with this approach is identifying what needs to be optimized. With numerous measures for each aspect of housing it is important to be clear on the key parameter to optimize (materials, energy or labor). The ideal scenario is a house with a long lifespan, resistance to humidity, with low energy consumption during its operation, and constructed in such a way that it can be deconstructed easily with a high percentage of the material available for recovery. However, there are many tradeoffs with any of these choices, and some are directly in conflict with each other. For example, a house with a 100 year lifespan compared to a house with a 50 year lifespan will result in half as much construction, if replacement is being considered. No conclusions were made with regards what the most appropriate indicators to use were and this is an area that needs further work.

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